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Meteorological Uncertainty of atmospheric Dispersion model results (MUD)

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Abstract

The MUD project addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as possibilities for optimum presentation to decision makers. Previously, it has not been possible to estimate such uncertainties quantitatively, but merely to calculate the 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for long-range atmospheric dispersion models.

The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model results. These uncertainties stem from e.g. limits in meteorological observations used to initialise meteorological forecast series. By perturbing e.g. the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced from which uncertainties in the various meteorological parameters are estimated, e.g. probabilities for rain. Corresponding ensembles of atmospheric dispersion can now be computed from which uncertainties of predicted radionuclide concentration and deposition patterns can be derived.

Key words

nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty, ensemble prediction

Meteorological Uncertainty of atmospheric Dispersion model results MUD

Final Report of Year One of the NKS-B MUD activity

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1. Introduction

The NKS-B project Meteorological Uncertainty of atmospheric Dispersion model results (MUD) addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as possibilities for presentation to decision makers. The duration of the project is two years, 2012–2014, and the present report describes the results of the first year.

Previously, it has not been possible to estimate such uncertainties quantitatively, but merely to calculate the 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for long-range atmospheric dispersion models. This is due to the fact that the quality of the latter models is limited by the quality of the NWP model data employed.

The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model results. These uncertainties stem from e.g. limits in meteorological observations used to initialise meteorological forecast series. By perturbing e.g. the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced from which uncertainties in the various meteorological parameters are estimated, e.g. probabilities for rain. Corresponding ensembles of atmospheric dispersion can now be computed from which uncertainties of predicted radionuclide concentration and deposition patterns can be derived.

In 2011, the Norwegian and the Danish meteorological institutes began running such meteorological ensemble systems operationally for geographical domains covering parts of Scandinavia. By using the output from such NWP ensembles, corresponding ensembles of atmospheric dispersion of radioactivity from an accidental release can be computed.

2. Selection of release scenarios

A selection of four nuclear power plants (NPPs) and the release scenario to be employed in MUD has been made. The following NPPs, which are all located in, or in vicinity of, the Nordic countries, were selected as hypothetical release points for the atmospheric dispersion model calculations:

- Ringhals
- Brokdorf
- Sellafield
- The future NPP in Kaliningrad

The same release scenario will be used for the selected NPPs. It is defined by: low heat release, 40 m release height, and 6-hour emission of the radionuclides Cs-134, I-131, Xe-135 and Pu-239. The detailed release scenario was prepared by DEMA.

3. Selection of meteorological scenarios

Four meteorological scenarios involving full forecast series of 54 hours and fulfilling the needs for variability have been found by examining archived data several years back in time. The scenarios involve windy cyclonic and low-wind anti-cyclonic conditions, as well as convective summer precipitation influencing the wet deposition, and thereby potentially producing large uncertainties in the resulting deposition patterns, cf. Table 1.

Table 1. Meteorological scenarios. The date and time indicate the start of the 54 hour forecast series (the meteorological analysis time), which is here identical with the start of the 6-hours release.

Date and time (UTC)	Comment
2011-05-20 18:00	Brokdorf affecting Denmark (frontal precipitation over Jutland), Sellafield Norway, Ringhals Sweden and Finland
2011-08-14 00:00	Brokdorf affecting Denmark (frontal precipitation over south Jutland), Sellafield Denmark, Ringhals Norway, Kaliningrad Sweden
2012-01-08 00:00	Ringhals affecting Denmark (low wind, no precipitation)
2012-03-07 00:00	Brokdorf affecting Denmark, Sellafield southern Norway, Ringhals Sweden and Norway, Kaliningrad Sweden and partly Finland

4. Description of the DMI meteorological EPS

The DMI meteorological Ensemble Prediction System (EPS), which is currently based on the HIRLAM numerical weather prediction model, involves 25 ensemble members. The horizontal resolution is 0.05° , corresponding to approximately 5.5 km, and vertically the model has 40 layers from the surface to 10 hPa (approximately 30 km above the sea surface). The ensemble HIRLAM model is nested into ECMWF's global model. The geographic domain is displayed in Fig. 1.

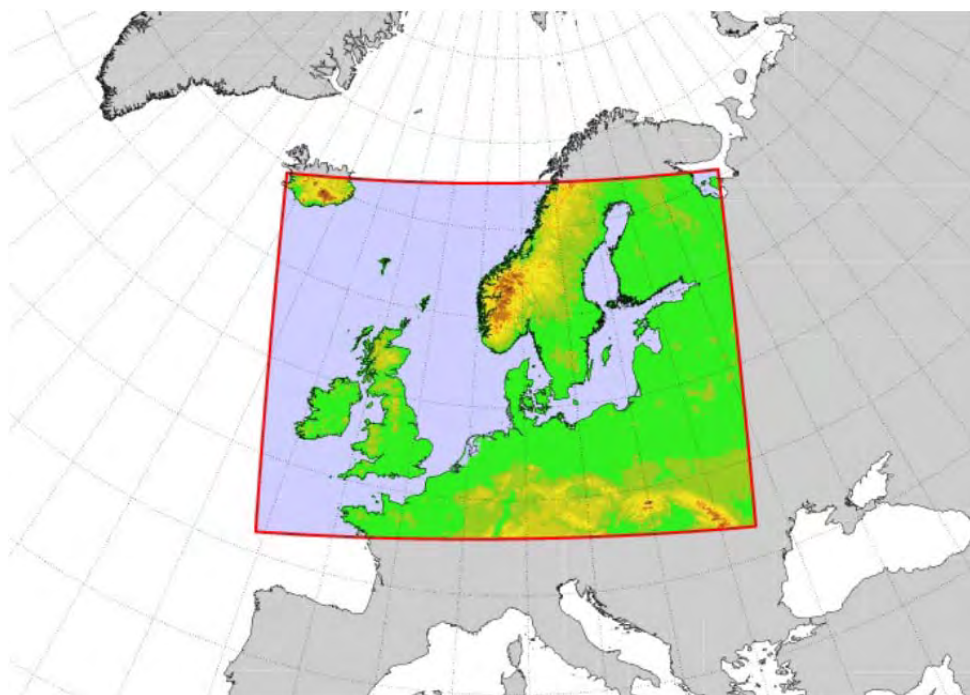


Figure 1. Geographic domain covered by the DMI EPS.

Meteorological forecast uncertainties arise from uncertainties in the initial and lateral boundary conditions and from model short-comings, particularly short-comings associated with parameterization of physical processes that take place on spatial scales that cannot be represented explicitly in the model. The initial condition uncertainty is assumed to be comparable to the forecast error for a short (6 or 12 h) forecast, and so perturbations

proportional to the forecast error are added to or subtracted from the initial conditions (Hou *et al.*, 2001). This approach is easily implemented, it can be generalized to also account for uncertainties in the lateral boundary conditions, it does not require input from a global ensemble prediction system, and the results are satisfactory compared to other, more advanced methods (Garcia-Moya *et al.*, 2011). The main drawback is that the number of perturbations is limited to four, if the estimated forecast errors are based on the two most recent deterministic ECMWF forecasts. Therefore, the initial condition perturbations are combined with model perturbations: 13 ensemble members use the STRACO cloud scheme (Sass, 2002), while the remaining 12 members use the Kain-Fritsch/Rasch-Kristjansson scheme (Kain, 2004; Rasch and Kristjansson, 1998); 12 members use the HIRLAM-version of the ISBA surface scheme (Rodriguez *et al.*, 2003), and 13 members use a modified version, referred to as “Newsnow” (Gollvik and Samuelsson, 2010). Finally, in 13 members the total contribution from all physical parameterizations is perturbed stochastically (Feddersen, 2009) in order to represent the otherwise unaccounted for uncertainty in the parameterizations, similarly to what has been done for ECMWF's ensemble prediction system for many years (Buizza *et al.*, 1999).

DMI's ensemble prediction system was made operational during April 2011. For short-range forecasts, i.e. up to two days in advance, the main uncertainties are those associated with clouds and convection, and so the main application of DMI EPS has been to provide forecasters at DMI with a tool to predict the risk of severe precipitation events (rain or snow) 12 to 36 hours in advance. Occasionally, there is also uncertainty associated with the wind field, typically in relation to passing weather fronts.

4.1 DMI EPS runs for MUD

The DMI EPS has been run for the four selected scenarios for 54 hour forecast periods. The corresponding weather situations are described in detail, and corresponding ensemble-statistical results calculated.

We note that in general the meteorological uncertainty increases with the forecast lead time. Hence, the plots that illustrate the ensemble spread in the following typically refer to the later parts of the forecast.

4.1.1 20 May 2011 case

At the start of the forecast (18 UTC), a low-pressure system is located northwest of Scotland with associated gale force winds south of it. The wind over Scandinavia is mostly from southwest, see Fig. 2. Later, a front with relative intense rainfall passes Denmark and southern Scandinavia. Figure 3 shows that there is little spread in the location of the front, but some spread in the intensity of the rainfall.

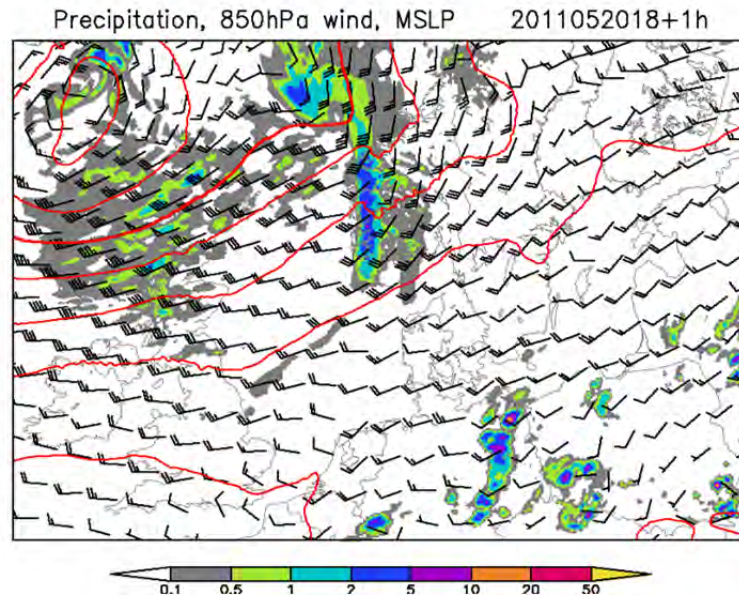


Figure 2. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 18 UTC, 20 May 2011.

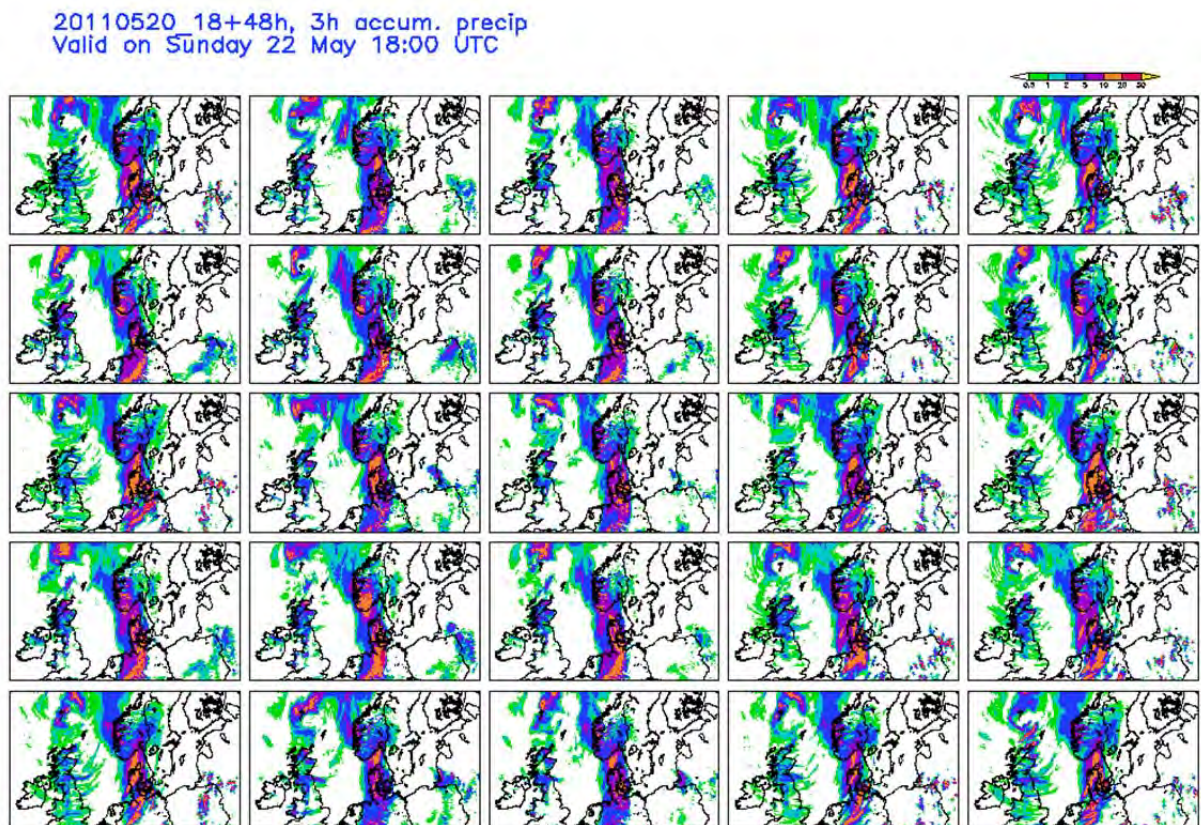


Figure 3. 25 ensemble members each showing precipitation accumulated between forecast hours 45 and 48. Contours at 0.5, 1, 2, 5, 10, 20 and 50 mm.

4.1.2 14 August 2011 case

A low pressure system is located west of the Faroe Islands, and a front is approaching Denmark and southern Scandinavia from the west. The flow over Scandinavia is south and southeasterly (Fig. 4). About 18 hours into the forecast, a secondary low and a quite intense rainfall develop just south of Denmark. The development varies between the members of the ensemble, affecting the spread in both rainfall and wind direction, particularly in the western part of the Baltic Sea (Figs. 5 and 6).

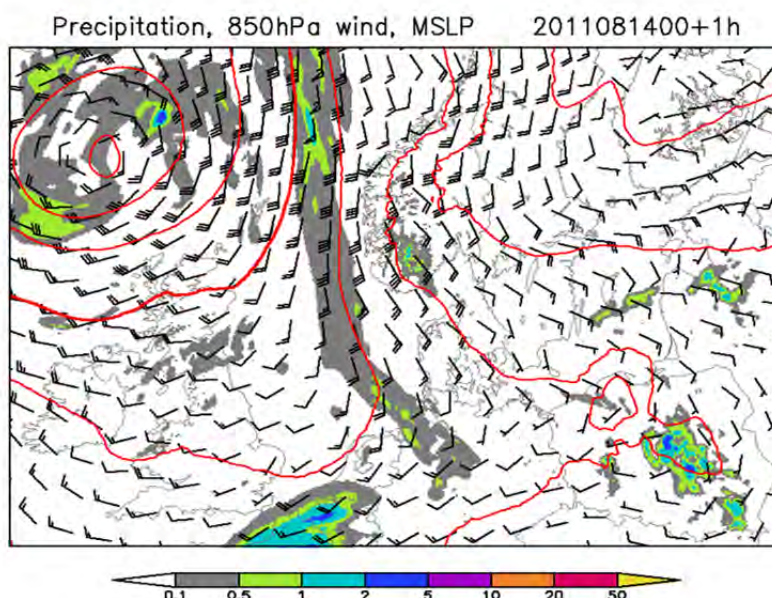


Figure 4. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 14 Aug 2011.

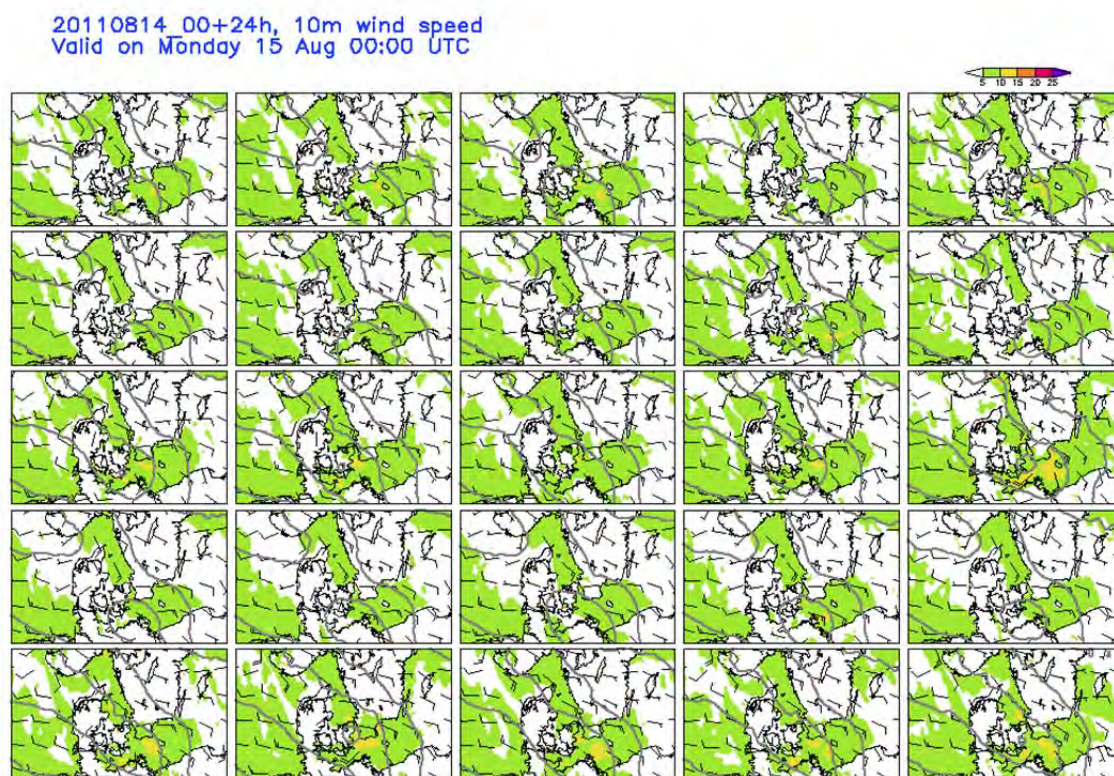


Figure 5. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble.

20110814 00+24h, 3h accum. precip
Valid on Monday 15 Aug 00:00 UTC

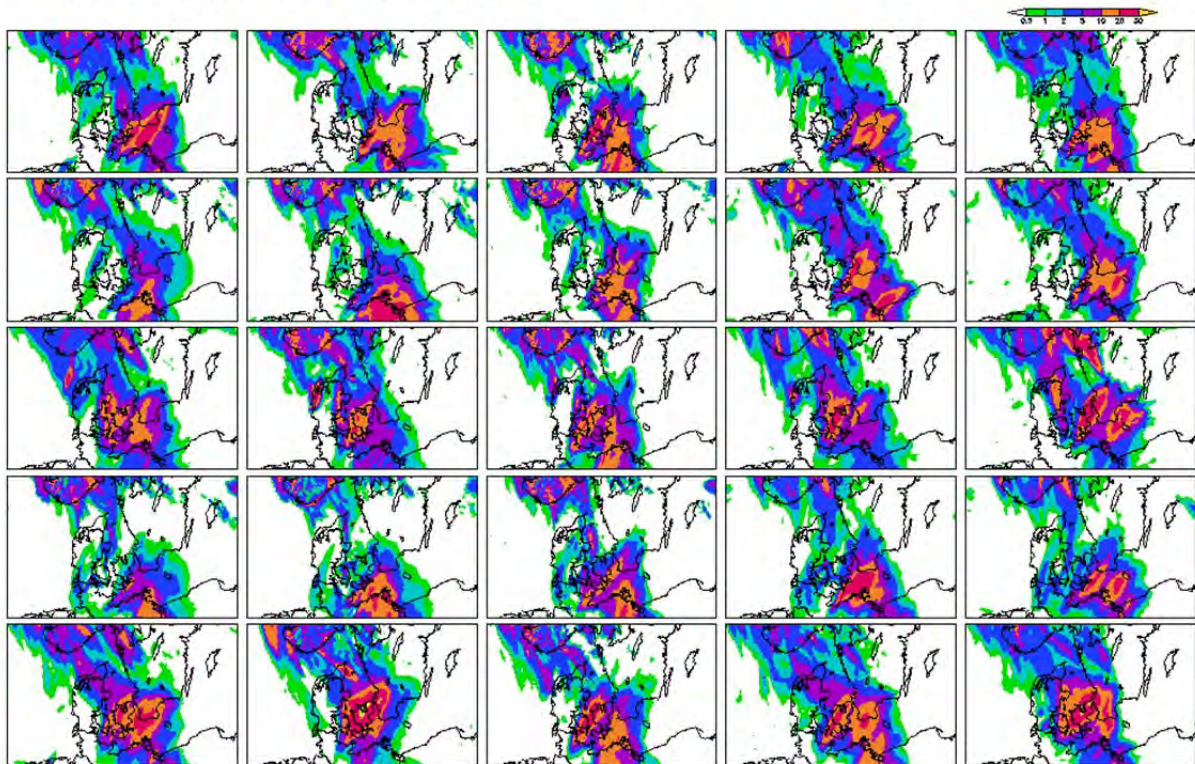


Figure 6. 25 ensemble members each showing precipitation accumulated between forecast hours 21 and 24. Contours at 0.5, 1, 2, 5, 10, 20 and 50 mm.

4.1.3 8 January 2012 case

In this case the wind over southern Scandinavia is relatively weak from directions between west and north. Figure 8 shows some spread in the 10 m wind field in southern Scandinavia 42 hours into the forecast. The spread results from uncertainty about the low located over Kattegat as illustrated in Fig. 9. There is also some precipitation associated with this low – rain in Denmark, snow in Sweden.

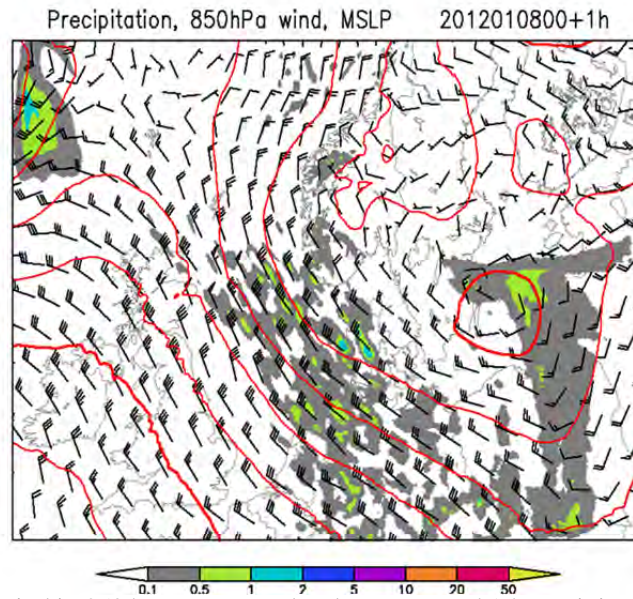


Figure 7. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 8 Jan 2012.

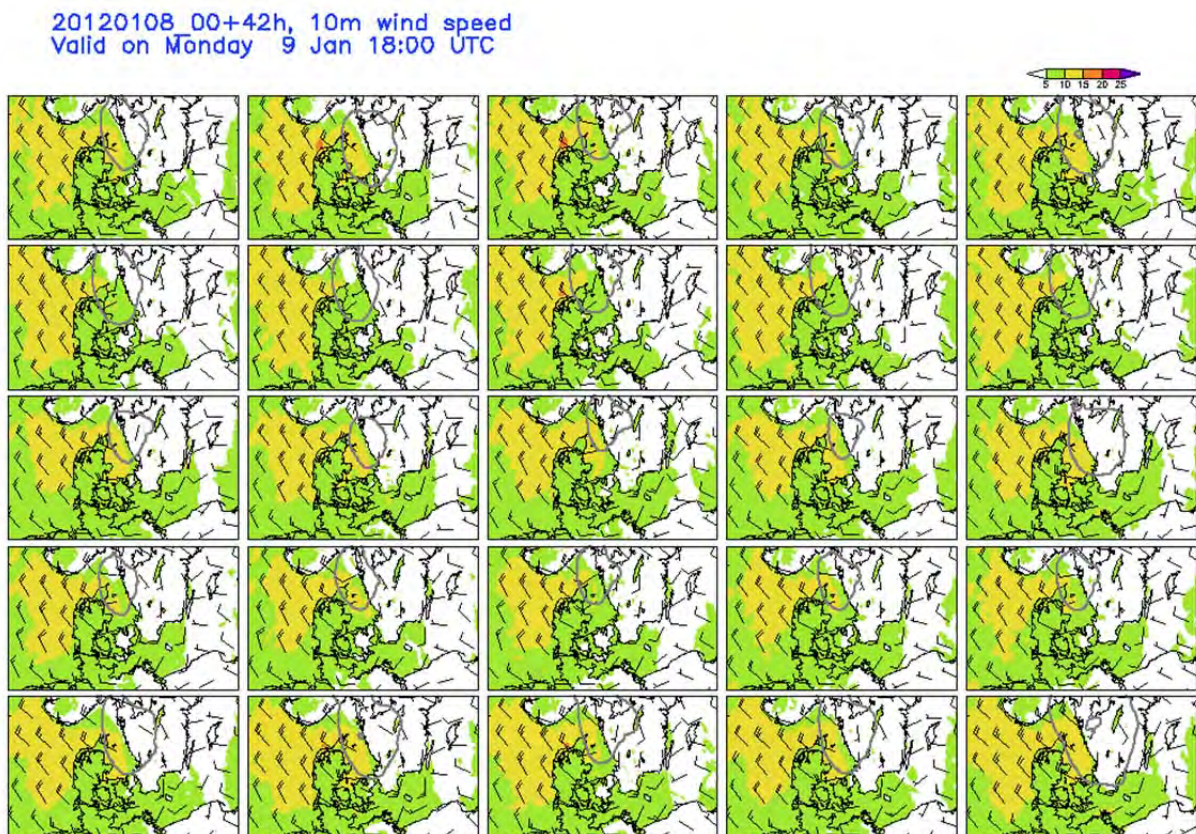


Figure 8. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble.

20120108_00+42h, MSLP
Valid on Monday 9 Jan 18:00 UTC

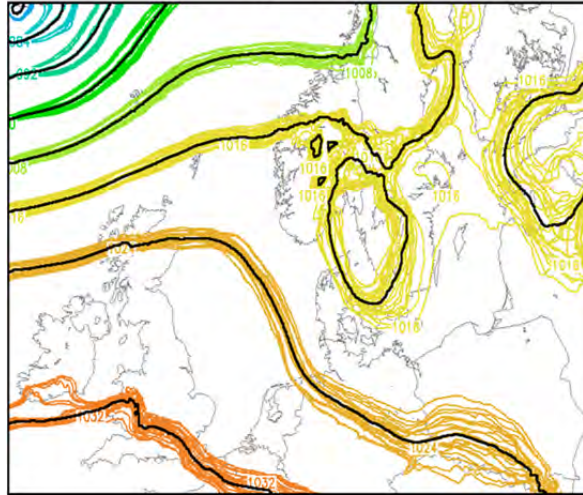


Figure 9. “Spaghetti map” showing mean sea level pressure for all members. Ensemble mean is shown as black contours.

4.1.4 7 March 2012 case

In the North Atlantic north of the Faroe Islands stormy conditions prevail. Over the British Isles and the North Sea the wind direction is southwesterly, while over Scandinavia the wind direction is mostly from the south (Fig. 10). Further east, over the Baltic States, the wind is weak and from a northerly direction. One day into the forecast the wind direction over Denmark and southern Norway changes to northeast following the passing of a cold front, while the wind direction over the rest of Scandinavia remains southerly for several hours. The ensemble spread remains remarkably small during the first day of the forecast (Fig. 11). It is not until the last hours of the forecast, when the wind is generally weak over southern Scandinavia, that we notice some spread between the ensemble members (Figs. 12 and 13).

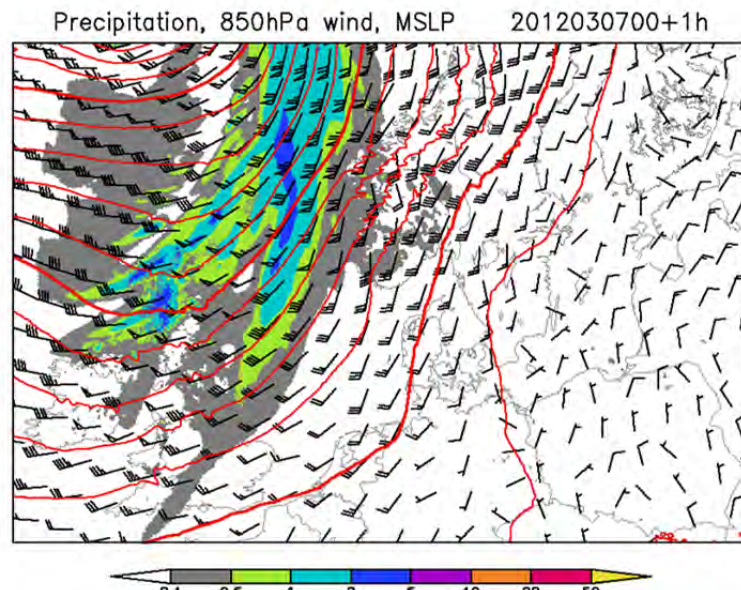


Figure 10. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 7 Mar 2012.

20120307_00+27h, 10m wind speed
Valid on Thursday 8 Mar 03:00 UTC

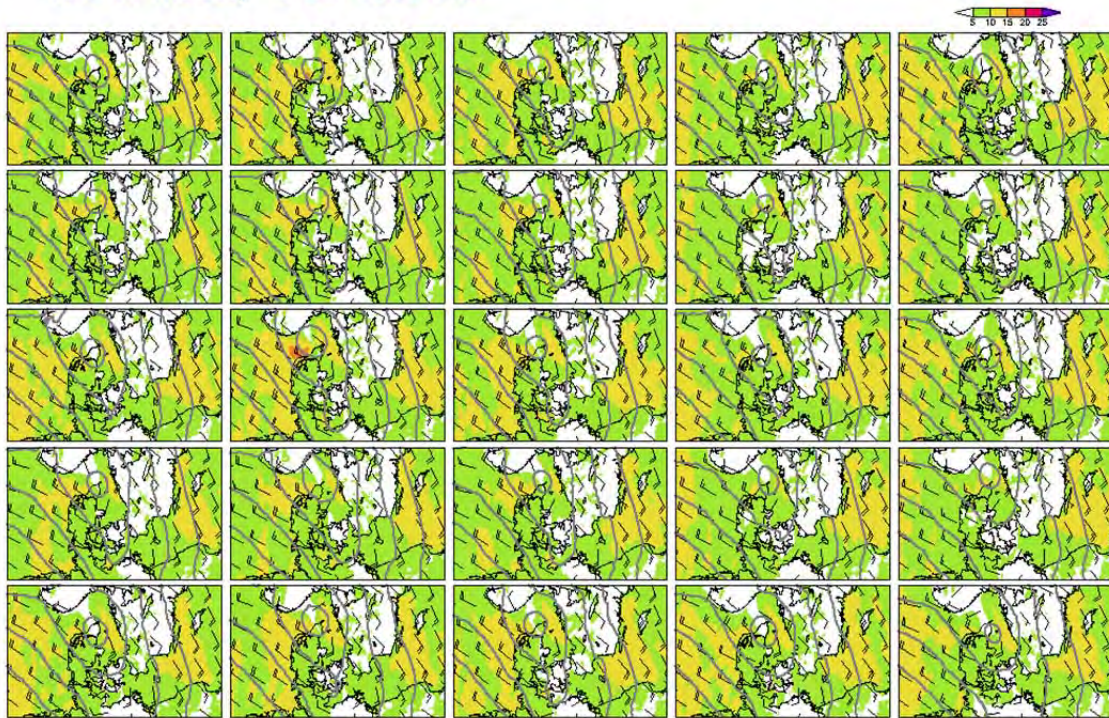


Figure 11. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble of 27 hour forecasts from 0 UTC, 7 Mar 2012.

20120307_00+45h, 10m wind speed
Valid on Thursday 8 Mar 21:00 UTC

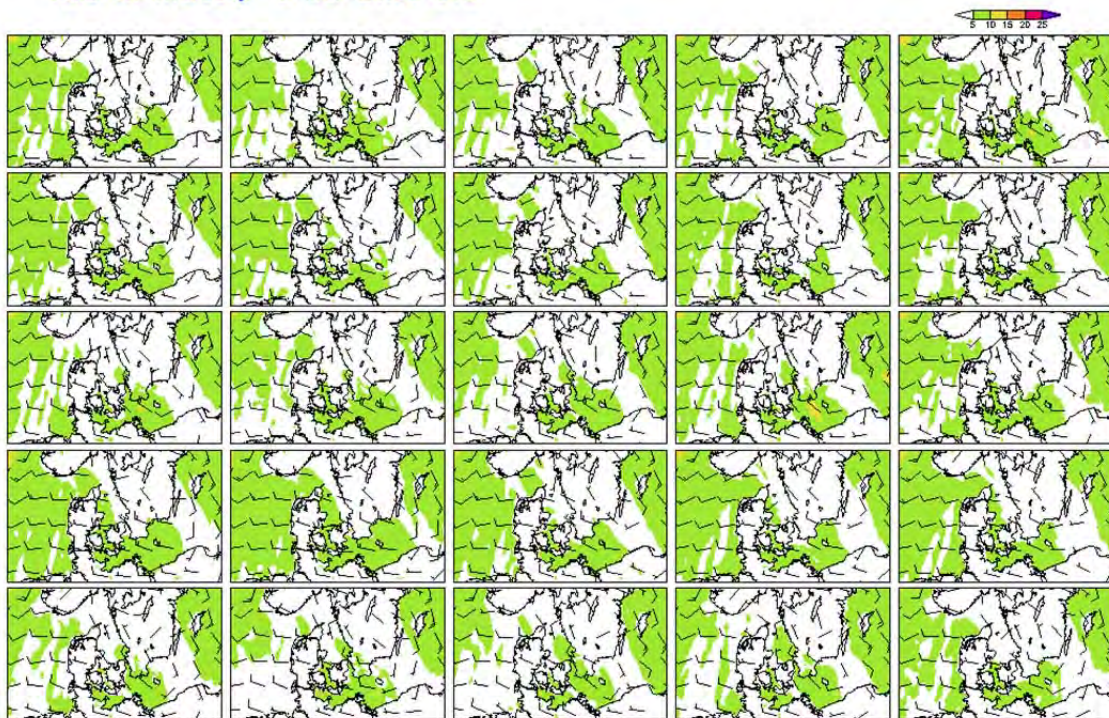


Figure 12. As Fig. 11, but for 45 hour forecasts from 0 UTC, 7 Mar 2012.

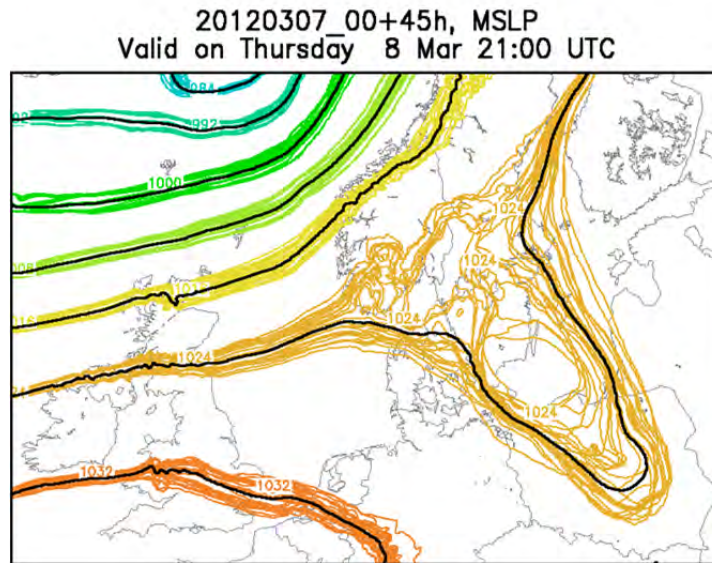


Figure 13. “Spaghetti map” showing mean sea level pressure for all members. Ensemble mean is shown as black contours.

5. Description of the GLAMEPS meteorological EPS

Glameps is the current operational ensemble prediction system at the Norwegian Meteorological Institute (met.no) in Oslo. The basic idea behind GLAMEPS is to account for all major sources of forecast inaccuracy up to 2.5 days using a multi model approach. GLAMEPS consists of several sub-ensembles as well as the deterministic run from the European Centre for Medium-Range Weather Forecasts (ECMWF) as shown in Fig. 14. There are two versions of HIRLAM, denoted as HirEPS_S and HirEPS_K where HirEPS_S employs the stratiform and convective cloud and precipitation scheme STRACO (Sass *et al.*, 1999; Unden *et al.*, 2002), and HirEPS_K uses the Kain-Fritsch schemes for deep cumulus (Kain and Fritsch, 1990; Kain, 2004; Calvo, 2007) and Rasch and Kristjansson (1998) for stratiform clouds and precipitation (Ivarsson, 2007). There is also one sub-ensemble based on Alaro. Both the Hirlam sub-ensembles and the Alaro sub-ensemble have an approximate resolution of 11 km and are nested in EPS from ECMWF. Also initial condition perturbations are taken from EPS from ECMWF (perturbation = EPS member – EPS control, then added to the appropriate LAM control member). The control members for the HIRLAM sub-ensembles have 6-hourly 3D-Var assimilation, while the Alaro control member is a downscaling of the EPS control member. However, all members (Hirlam and Alaro) have their own surface assimilation. With each of the three sub-ensembles with Hirlam and Alaro having 12 + 1 members, the first 36 of 50 members from ECMWF EPS are used as boundary conditions for GLAMEPS. The remaining 14 members are added to GLAMEPS as they are, we call this sub-ensemble ECEPS. This gives a total of 54 members, so quite comparable in ensemble size to EPS from ECMWF. GLAMEPS is run every day at ECMWF at 06 and 18 UTC, using initial conditions and lateral boundary conditions from 6 hours before. The main output products are probability forecasts in grib2 displayed at the website glameps.org. 3D fields can be downloaded from ECMWF, but this needs to be done regularly as the 3D fields are not stored but are available only for a few days. This pure model output is presently in grib1-format.

The main challenge for a regional EPS is to produce significantly better forecast in the short range than the best available global forecast. GLAMEPS is therefor compared against EPS from ECMWF. Different probabilistic scores are computed for GLAMEPS and compared to

EPS with one example given in Fig. 15. Figure 15 shows the CRPSS (continuous ranked probability skill score) for GLAMEPS (red) and EPS (black) for 10 m wind speed over Europe from February 2012 to September 2012. EPS is used as reference, hence it lies on the zero line. Positive values for GLAMEPS means that it scores better than EPS from ECMWF, and negative values that it scores worse. As can be seen from this figure, the improvement for GLAMEPS is between 0 to ~25%, compared to EPS for all period except some strange behavior in February/March. Looking closer at this period it turned out that also EPS showed big fluctuations in quality during this period (not shown), so this was not something specific for GLAMEPS. Also other weather parameters show similar scores as wind (not shown). Therefore it can be concluded that GLAMEPS with its present set-up is able to produce significantly better forecasts than EPS from ECMWF on the desirable forecast length of up to 2.5 days for Europe.

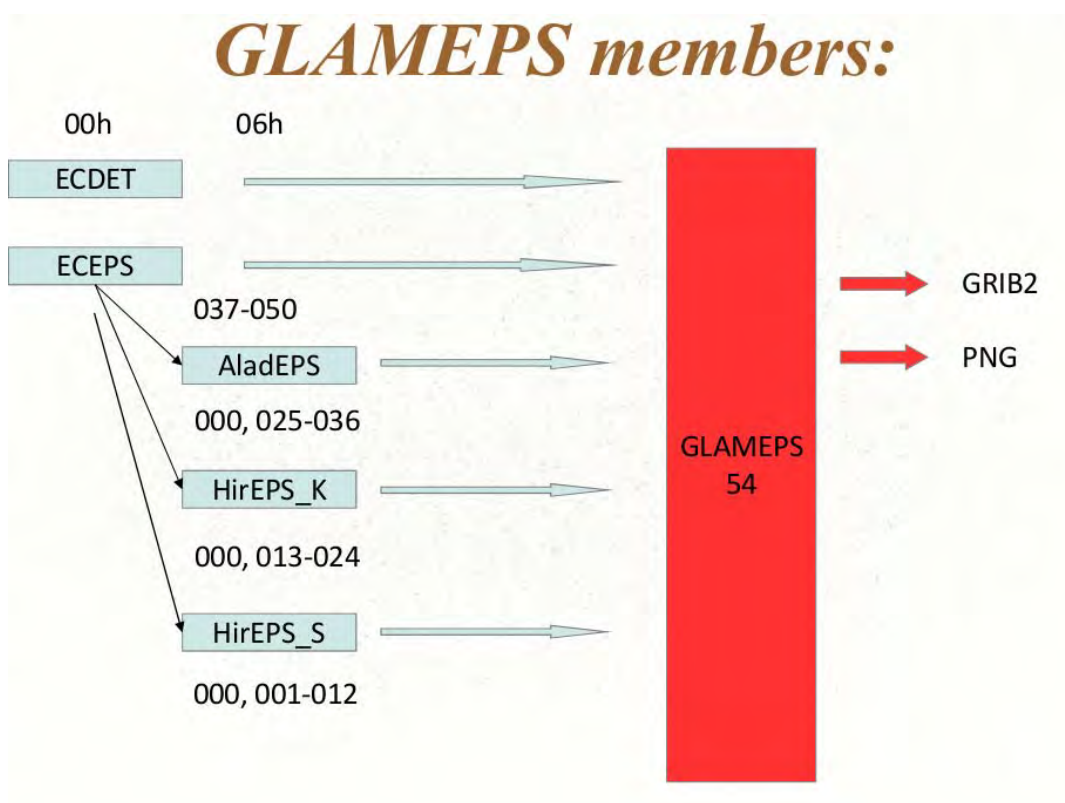


Figure 14. Schematic illustration of GLAMEPS, consisting of the four sub-ensembles HirEPS_S, HirEPS_K, AladEPS and ECEPS, as described in the text.

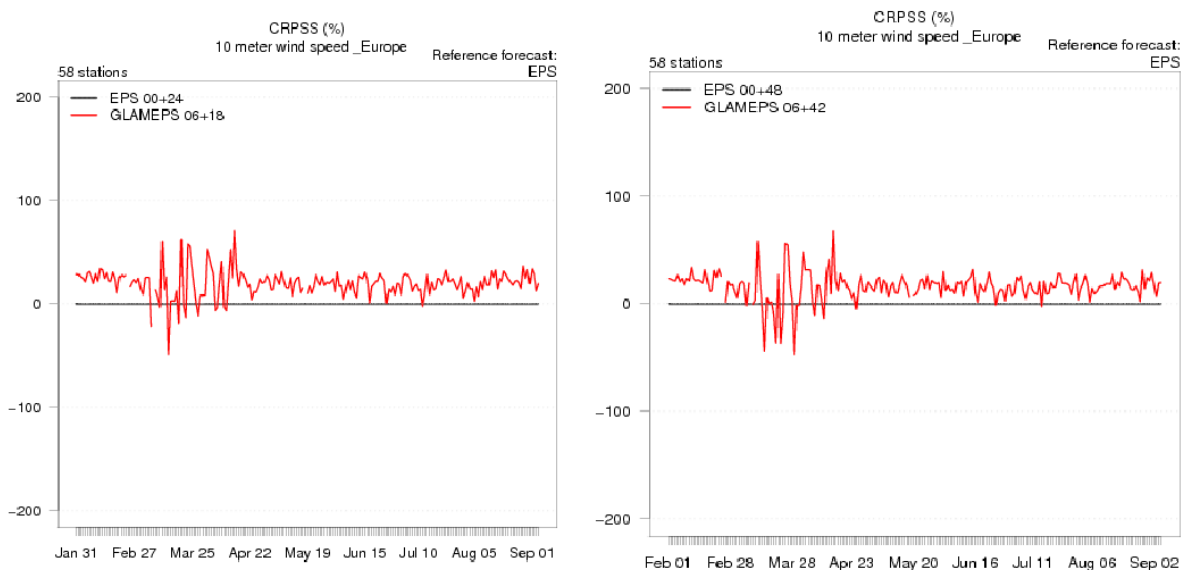


Figure 15. CRPSS for GLAMEPS (red) and EPS from ECMWF (black) for 10 m wind speed over Europe, from February to September 2012. EPS from ECMWF is used as reference, hence it lies on the zero line. Left +18h, right +42h.

6. Description of the DMI atmospheric dispersion model DERMA

The Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen *et al.*, 2007; Sørensen, 1998) is a comprehensive numerical regional and meso-scale atmospheric dispersion model developed at the Danish Meteorological Institute (DMI). The model is used operationally for the Danish nuclear emergency preparedness, for which the Danish Emergency Management Agency (DEMA) is responsible (Hoe *et al.*, 2002). Besides, the model is employed for veterinary emergency preparedness (Sørensen *et al.*, 2000, 2001; Mikkelsen *et al.*, 2003; Gloster *et al.*, 2010a, 2010b), where it is used for assessment of airborne spread of animal diseases, e.g. foot-and-mouth disease. DERMA may also be used to simulate atmospheric dispersion of chemical substances, biological warfare agents and ashes from volcanic eruptions, and it has been employed for probabilistic nuclear risk assessment (Lauritzen *et al.*, 2006, 2007; Baklanov *et al.*, 2003; Mahura *et al.*, 2003, 2005).

The main objective of DERMA is to predict the dispersion of a radioactive plume and the accompanied deposition. However, the model may also be used in situations where an increased level of radioactivity has been measured but no information is received on radioactive releases. In such cases, inverse (adjoint) modelling may be applied whereby potential sources of radioactivity may be localised and release rates estimated.

DERMA has been evaluated against available measurement data from accidental releases and against the European Tracer Experiment (ETEX) involving controlled releases of a tracer gas detected by nearly 200 measurement stations in Europe. ETEx was accompanied by model validations (Graziani *et al.*, 1998) in which DERMA performed well among 28 models from European countries, USA, Canada and Japan. DERMA has also been verified against the Algeciras incidence involving incineration of a medical radioactive source followed by atmospheric dispersion over the Mediterranean. Currently, DERMA takes part in the EU ensemble modelling activities for nuclear emergency preparedness (Galmarini *et al.*, 2004a, 2004b).

The three-dimensional model is of Lagrangian type making use of a hybrid stochastic particle-puff diffusion description, and it is currently capable of describing plumes at downwind distances greater than about 20 km and up to the global scale (Sørensen *et al.*, 1998). The model utilizes aerosol size dependent dry and wet deposition parameterisations as described by Baklanov and Sørensen (2001).

DERMA makes use of analysed and forecasted meteorological data from the numerical weather prediction model DMI-HIRLAM covering Denmark, Greenland and the Faeroes (Sass *et al.*, 2002) and from the global model developed and operated by the European Centre for Medium-range Weather Forecasts (ECMWF). DMI-HIRLAM utilises nesting technique implying a horizontal resolution ranging from 15 km over the Arctic and Europe down to 3 km over northern Europe.

DERMA is interfaced with the Accident Reporting and Guidance Operational System (ARGOS) (Hoe *et al.*, 1999; 2002), a PC based nuclear decision-support system developed by DEMA and the Prolog Development Center A/S (PDC). ARGOS is currently used in 13 countries. For local-scale modelling of atmospheric dispersion ARGOS makes use of the RIMPUFF system (Mikkelsen *et al.*, 1997), which is developed at the Risø National Laboratory. In Denmark, RIMPUFF utilises high-resolution data (currently 3 km) from DMI-HIRLAM.

The integration of DERMA in the ARGOS system is effectuated through automated online digital communication and exchange of data between the ARGOS system and the DMI server. To this purpose DMI's operational ftp-server (with a backup server) is used as the point of contact. The ARGOS system prepares and uploads a description of the release. This automatically triggers DERMA to run on an operational server (involving a backup) using this information as well as data from each of the various operational meteorological models thereby providing a mini-ensemble of dispersion forecasts. While running, the DERMA system issues status messages to ARGOS, and finally, results are made available. In fact, it is "invisible" to the ARGOS user that the long-range dispersion calculation is performed on a remote on-line connected computer.

6.1 DERMA runs for MUD

The DMI atmospheric dispersion model, the Danish Emergency Response Model of the Atmosphere (DERMA), has been run for the selected release scenario for the four NPPs and the four meteorological scenarios selected, each involving the 25 ensemble members of the DMI meteorological EPS. This amounts to 400 model runs in total. A single result of these calculations is shown in the figure below. More figures are available from Appendix A. As expected, in some cases the dispersion model results vary substantially across the ensemble, in others only little variation is observed between the dispersion model ensemble members.

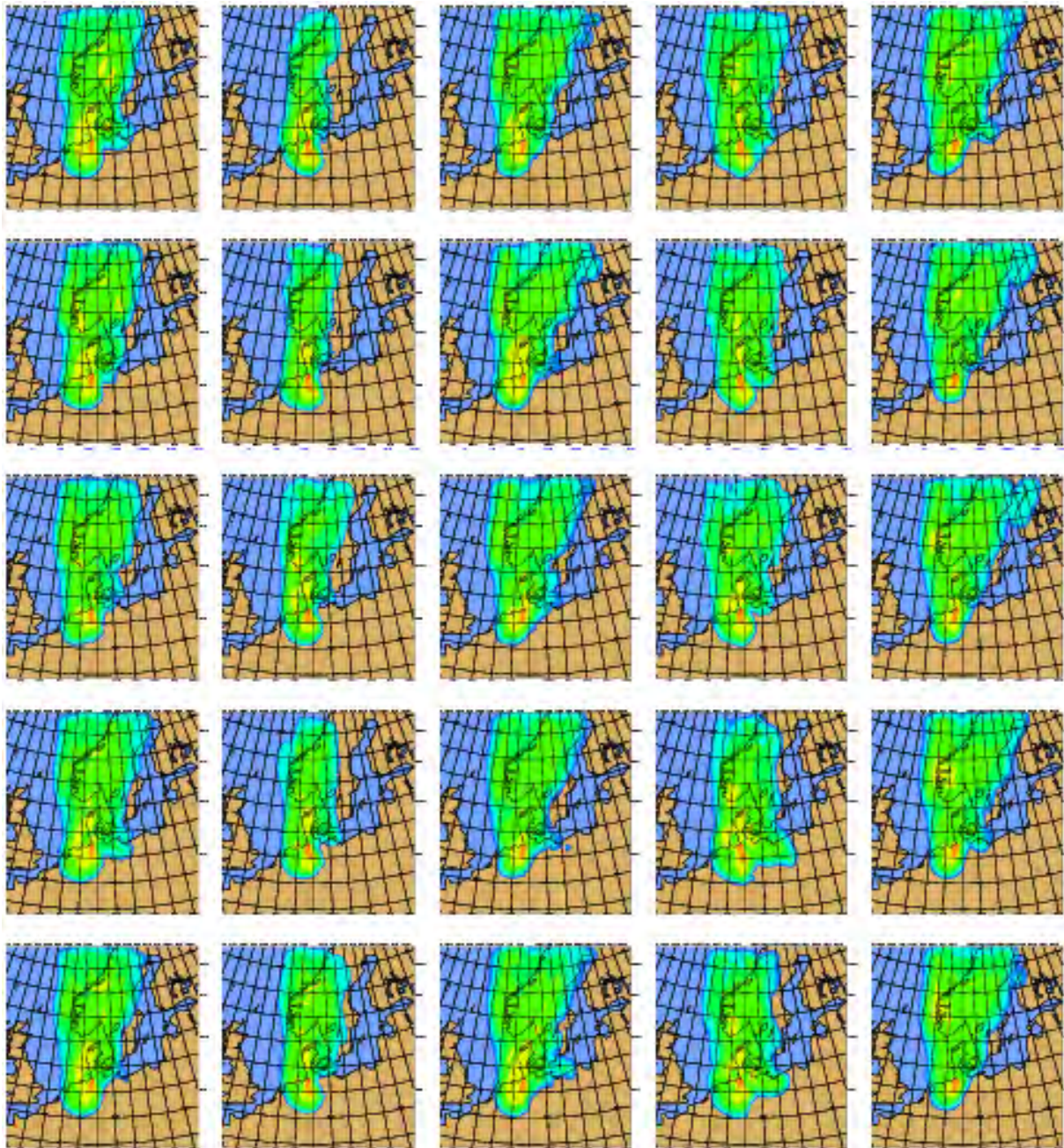


Figure 16. Ensemble of atmospheric dispersion model calculations. Total accumulated deposition of Cs-134 corresponding to a release from Brokdorf on 2011-05-23, 00 UTC.

7. Description of the Met.no atmospheric dispersion model EEMEP

The EEMEP model has been developed at met.no in 2012 to replace the previous SNAP model (Bartnicki *et al.*, 2011) in operational applications. It is a part of the EMEP MSC-W model (Simpson *et al.*, 2012) which has been routinely run for many years at met.no for the needs of Geneva Convention on the Long Range Transport of Air Pollutants. The acronym EMEP stands for European Monitoring and Assessment Program under Geneva Convention and MSC-W stands for Meteorological Synthesizing Centre West of EMEP. The MSC-W has been hosted by the Norwegian Meteorological Institute since the beginning of the EMEP programme in 1979. The main task of the centre is to model transboundary fluxes of acidifying and eutrophying air pollution, photochemical oxidants and particulate matter. The EMEP model has been developed in the Eulerian framework which has many advantages for the models with complicated chemistry. The EEMEP (Emergency EMEP) model is using the

same routines for advection, diffusion and partly deposition processes as the EMEP model, but it takes into account radioactive debris emitted in case of nuclear accident or explosion. The EEMEP model is also used for simulating atmospheric transport and deposition of volcanic ash, but here only nuclear applications are relevant. The Eulerian framework has some advantages for simulating transport of pollutants in the large and especially global scale and in case of long term release. The EEMEP model grid system is flexible in spatial and vertical resolution and can be used not only in the global/regional scale, but in much smaller scales as well. Therefore, it was possible to perform EEMEP simulations with the ensemble meteorological data received from the Danish Meteorological Office. Atmospheric dispersion of gases, noble gases and particles of different size and density can be simulated with EEMEP model. The standard computational domain covers the entire earth with input meteorological data from ECMWF. Operational means that two runs are performed every day with the EEMEP model for selected eight nuclear power plants as the potential sources plus two locations of the potential nuclear explosion. Default source terms are used for routine everyday runs having in mind that the direction and time of the transport are the most important factors in the initial phase of potential accident or explosion. In case of emergency, the EEMEP model can be run at any time with much more detailed and extended source term, the latest available.

The EEMEP model is relatively new at met.no and its results have not been systematically compared with measurements. Such a comparison based on Fukushima accident simulations will be performed in 2013. However, the results of EEMEP model have been compared in 2012 with the SNAP model results showing similar patterns of deposition and concentration.

7.1 EEMEP runs for MUD

Unfortunately, three-dimensional historical meteorological data from the GLAMEPS ensemble system necessary for selected MUD scenarios were not available at met.no in the year 2013. Therefore, we have used the same meteorological fields as our Danish colleagues (thanks for their help) from DMI EPS, described in the previous chapters. These meteorological ensemble data consist of 25 members, and EEMEP dispersion model was run for each individual member of the ensemble. The forecast time was 54 hours for all runs. The eEMEP runs were performed for four sources – nuclear power plants: Ringhals, Kaliningrad, Sellafield and Brokdorf. As agreed during the first MUD meeting, the same release scenario was used for the selected NPPs. It was defined by: low heat release, 40 m release height, and 6-hour emission of four radionuclides Cs-134, I-131, Xe-135 and Pu-239.

An example of EEMEP simulations for Sellafield as the source and meteorological scenario from 20110523 00 UTC are shown in Fig. 17. In this example, the total deposition of Cs-134 is shown. For all members of the ensemble, the Cs released in Sellafield travels in North-East direction reaching the Norwegian territory. The deposition maps in Fig. 17 differ from each other, but it is interesting to notice that some similarities can be observed for the maps in the same column, whereas differences are relatively larger for the maps belonging to the same row. The reason is probably the relatively similar perturbed initial conditions for ensemble members in the same columns. In general, deposition maps for Cs-134 obtained for eEMEP model simulations are similar to those calculated from DERMA model simulations.

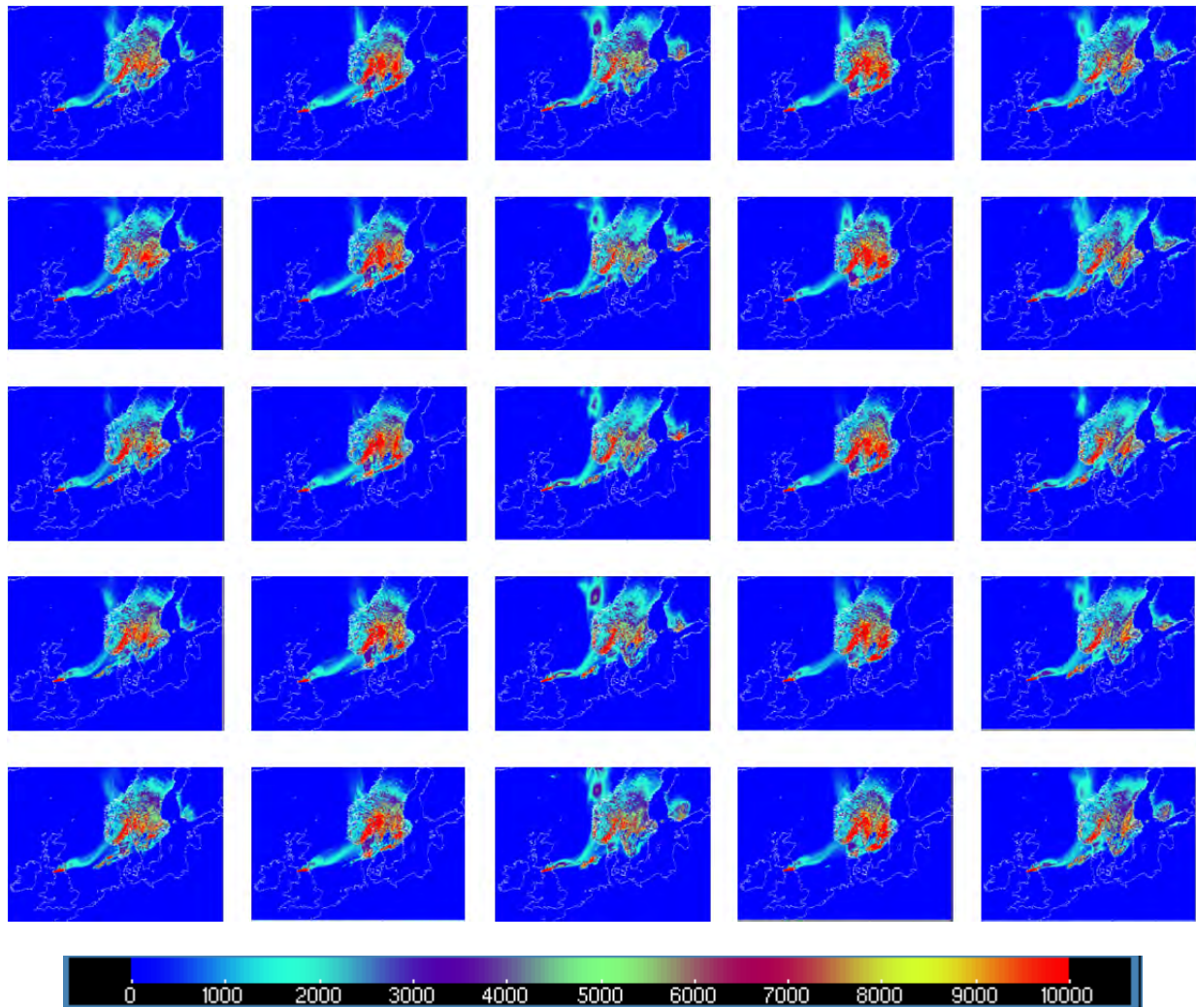


Figure 17. The results of EMEP model simulations for NPP Sellafield as the source and meteorological scenario from 20110523 00 UTC. Total (dry + wet) deposition of Cs-134 (Bq m^{-2}) is shown for each of 25 meteorological ensemble members.

More results of EMEP model simulations are presented in Appendix B. These results are only presented for the meteorological scenario from 2011. Unfortunately, some problems have occurred with the conversion of 2012 Danish meteorological data to the EMEP grid system and these simulations will be performed in 2013.

8. Uncertainties of atmospheric dispersion for decision support

Possibilities for the use and presentation of uncertainties in a nuclear decision support system (DSS) have been thoroughly investigated, some of which are based on the meteorological use of EPS for weather forecasting. It has finally been decided to apply the following two methods:

- *Max, mean and min influence areas:* For each radionuclide and each output time, the maximum, mean and minimum values will be calculated for each of the following fields: time-integrated concentration, instantaneous concentration and total accumulated deposition. The max, or worst case scenario, will be obtained by selecting the max values of the ensemble members at each grid point, and similarly for the min field. Obviously, the max and min fields are not solutions to the governing equations. However, from a decision-support point of view those fields may prove to be very useful. The max and min fields may be used also for estimation of earliest and latest time of arrival.
- *Threshold-value based areas:* For a given threshold value, the 2-D probability field for exceeding this value will be calculated. This procedure will be carried out for each radionuclide and every output time step for each of the fields: time-integrated concentration, instantaneous concentration and total accumulated deposition. For an automatic operational system, these threshold values, which will be radionuclide dependent, should be provided by the nuclear DSS in the request file to the meteorological service carrying out the long-range atmospheric dispersion calculations. For demonstration purposes in MUD, these values will be estimated by DTU Nutech, SSM and DEMA for selected radionuclides.

There are potentially large uncertainties associated with the source term estimation. The presentation of such uncertainties in nuclear DSSs could utilize the same approaches developed in MUD. However, though relevant for emergency preparedness, these subjects are considered outside the scope of MUD, which focuses on meteorological uncertainties and their effects on atmospheric dispersion.

The numerical results of MUD will be made available in a format which can be imported in the ARGOS DSS, which will thereby host a demonstration of MUD results.

9. Dose calculations

Atmospheric dispersion model calculations of anticipated radionuclide releases from a nuclear accident should assist decision makers in assessing contamination levels, to provide information on the radiation hazards, and possibly to facilitate decisions on protective actions. Such actions, to be implemented in the early phases of the accident can be e.g. sheltering or evacuation.

Precautionary protective actions in anticipation of a large release or in acute phases of an imminent or ongoing release, where the source term can more reasonably be estimated, the scale and duration of the countermeasures should be optimized to reduce the radiation exposures while avoiding unnecessary interventions. Decision on possible interventions should therefore be based on an assessment of the avoidable radiation dose ΔE . Reference levels for optimized intervention levels are provided by e.g. IAEA (IAEA, 2011), and a countermeasure is justified provided the expected avoidable dose exceeds the reference level, i.e.

$$\langle \Delta E \rangle = \frac{1}{N} \sum \Delta E = \Delta E_{IL} .$$

Here, the expectation value $\langle \Delta E \rangle$ is determined as the average value over a set of N independent estimates of the avoidable dose. In case of atmospheric dispersion model calculations, this amounts to estimating the ensemble average over the set of such calculations.

The atmospheric dispersion model calculations yield time-dependent radionuclide activity concentrations in air, ρ_i , and on the ground, c_i , stemming from dry and wet depositions during plume passage. In addition, from the radionuclide concentrations in air the time-integrated (surface) air concentration and the total, accumulated deposition can be inferred,

$$\chi_i = \int_0^\infty dt' \rho_i$$

$$c_{i,\infty} = \int_0^\infty dt' \left(\frac{dc_i}{dt} \right)_{dep},$$

where $\left(\frac{dc_i}{dt} \right)_{dep}$ is the removal rate from the plume due to deposition and the time integration extends over the plume passage time.

Considering sheltering and evacuation countermeasures, three different pathways contribute to the avoidable radiation doses: external radiation from the plume, from the ground, and inhalation doses. These radiation doses depend linearly on the radionuclide concentrations in the air and on the ground. For sheltering, the avoidable dose can be written as

$$\begin{aligned} \Delta E &= \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh} \\ \Delta E &= \sum_i \{ (1 - L_{plume}) e_{plume,i} + (1 - F) B e_{inh,i} \} \chi_i \\ &+ \sum_i (1 - L_{ground}) e_{ground,i} \int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t') \end{aligned}$$

where the applied dose and dose reduction factors are provided in tables 2 and 3, and where the sums are over the contributing radionuclides. Similarly, for evacuation the avoidable dose is given by

$$\begin{aligned} \Delta E &= \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh} \\ &= \sum_i \{ e_{plume,i} + B e_{inh,i} \} \chi_i \\ &+ \sum_i e_{ground,i} \int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t') \end{aligned}$$

The radiation doses from radioactive materials deposited on the ground may be simplified by employing

$$\int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t') \approx (t - \frac{1}{2}T) c_{i,\infty},$$

where T is the plume passage time and t is the duration of the intervention, assumed to be longer than the plume passage time. With this approximation, the avoidable doses from sheltering and evacuation becomes

Sheltering

$$\Delta E = \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh}$$

$$\Delta E = \sum_i \{(1 - L_{plume})e_{plume,i} + (1 - F)Be_{inh,i}\}\chi_i$$

$$+ \sum_i (1 - L_{ground})e_{ground,i} (t - \frac{1}{2}T) c_{i,\infty}$$

Evacuation

$$\Delta E = \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh}$$

$$= \sum_i \{e_{plume,i} + Be_{inh,i}\}\chi_i$$

$$+ \sum_i e_{ground,i} (t - \frac{1}{2}T) c_{i,\infty}$$

As described in the previous section, uncertainties of atmospheric dispersion model calculations can be presented in different ways, e.g. by displaying both the expected (mean) levels of radionuclide concentrations as well as a high value (a high percentile) of the concentrations, derived from the ensemble of calculation results.

As intervention should be based on avoidable doses, for decision support it will be more appropriate to display dose values. In this case, the ensemble mean value of avoidable dose will allow for optimizing the area (other factors not considered) for implementing the countermeasure while the high value of avoidable dose provides an estimate of the maximum influence area. The reference values for intervention become threshold values for decision on countermeasures, as shown schematically in Fig. 18 below.

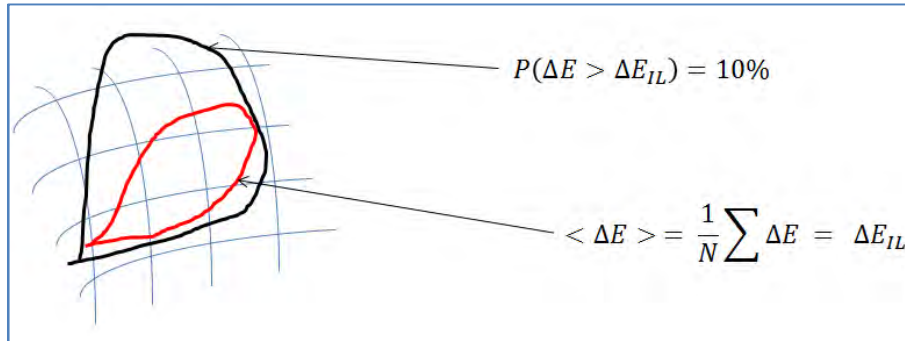


Figure 18. Schematic illustration of envelopes of the ensemble mean and the 10% probability of exceeding an intervention level.

Table 2. Quantities used for dose calculations.

Field	Symbol	Unit
Surface air concentration	ρ_s	Bq m ⁻³
Time-integrated surface air concentration	χ	Bq m ⁻³ s
Deposition (dry+wet)	$c = c_D + c_W$	Bq m ⁻²
Building location factor	L	-
Building filtration factor	F	-
Breathing rate	B	m ³ s ⁻¹

Table 3. Effective dose conversion factors for external gamma radiation from a semi-infinite plume and an infinite plane surface, and for inhalation.

Radionuclide	$e_{\gamma,plume}$ [Sv m ³ Bq ⁻¹ s ⁻¹]	$e_{\gamma,ground}$ [Sv m ² Bq ⁻¹ s ⁻¹]	$e_{inh}(50)$ [Sv Bq ⁻¹]
⁸⁵ Kr	1.4·10 ⁻¹⁶	-	-
⁸⁷ Kr	2.0·10 ⁻¹⁴	-	-
⁸⁸ Kr	5.7·10 ⁻¹⁴	-	-
⁹⁰ Sr	-	-	1.6·10 ⁻⁷
¹⁰³ Ru	2.7·10 ⁻¹⁴	3.1·10 ⁻¹⁶	3.0·10 ⁻⁹
¹⁰⁶ Ru	1.1·10 ⁻¹⁴	1.4·10 ⁻¹⁶	6.6·10 ⁻⁸
¹³¹ I	2.1·10 ⁻¹⁴	2.6·10 ⁻¹⁶	7.4·10 ⁻⁹
¹³² Te	1.1·10 ⁻¹⁴	1.6·10 ⁻¹⁵	2.0·10 ⁻⁹
¹³³ Xe	1.9·10 ⁻¹⁵	-	-
¹³⁵ Xe	1.3·10 ⁻¹⁴	-	-
¹³⁴ Cs	8.5·10 ⁻¹⁴	1.0·10 ⁻¹⁵	2.0·10 ⁻⁸
¹³⁶ Cs	1.1·10 ⁻¹³	3.0·10 ⁻⁹	2.8·10 ⁻⁹
¹³⁷ Cs	3.1·10 ⁻¹⁴	3.9·10 ⁻¹⁶	3.9·10 ⁻⁸
²³⁹ Pu	-	-	1.6·10 ⁻⁵

10. Conclusions

The MUD project addresses assessment of uncertainties of atmospheric dispersion model predictions caused by meteorological uncertainties, as well as possibilities for presentation to decision makers.

A selection of four NPPs has been made as hypothetical release points for atmospheric dispersion model calculations. The NPPs are located in, or in vicinity of, the Nordic countries. The release scenario is the same for all cases. It is defined by low heat release, 40 m release height, and 6-hour emission of the radionuclides Cs-134, I-131, Xe-135 and Pu-239.

Four meteorological scenarios involving full forecast series of 54 hours and fulfilling the needs for variability have been selected. The scenarios involve windy cyclonic and low-wind anti-cyclonic conditions, as well as convective summer precipitation influencing the wet deposition, and thereby potentially producing large uncertainties in the resulting deposition patterns.

The DMI atmospheric dispersion model DERMA, and the Met.no dispersion model EEMEP have been run for the selected release scenario for the four NPPs and the four meteorological scenarios selected, each involving the 25 ensemble members of the DMI meteorological EPS. As expected, in some cases the dispersion model results vary substantially across the ensemble, in others only little variation is observed between the dispersion model ensemble members.

Possibilities for the use and presentation of uncertainties in a nuclear decision support system have been thoroughly investigated, some of which are based on the meteorological use of EPS for weather forecasting.

10.1 Future work

As part of the project, it will be discussed with the radiation protection authorities taking part in the project how best to present the uncertainties, i.e. the distribution of model results, for decision makers.

Methods will be developed for computation of the meteorological uncertainties pertaining to simulations of atmospheric dispersion of radioactivity from accidental releases. Possibilities for optimum presentation to decision makers will be further investigated and described, and the methods developed will be applied to case studies.

The project will include a literature study on ensemble prediction for atmospheric dispersion.

Interactive communication between a national meteorological service and a nuclear decision-support system, using ARGOS as an example, will be examined as well as use of automatic procedures. Accordingly, the numerical results of MUD will be made available in a format which can be imported in ARGOS, which will thereby host the demonstration of MUD results.

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Disclaimer

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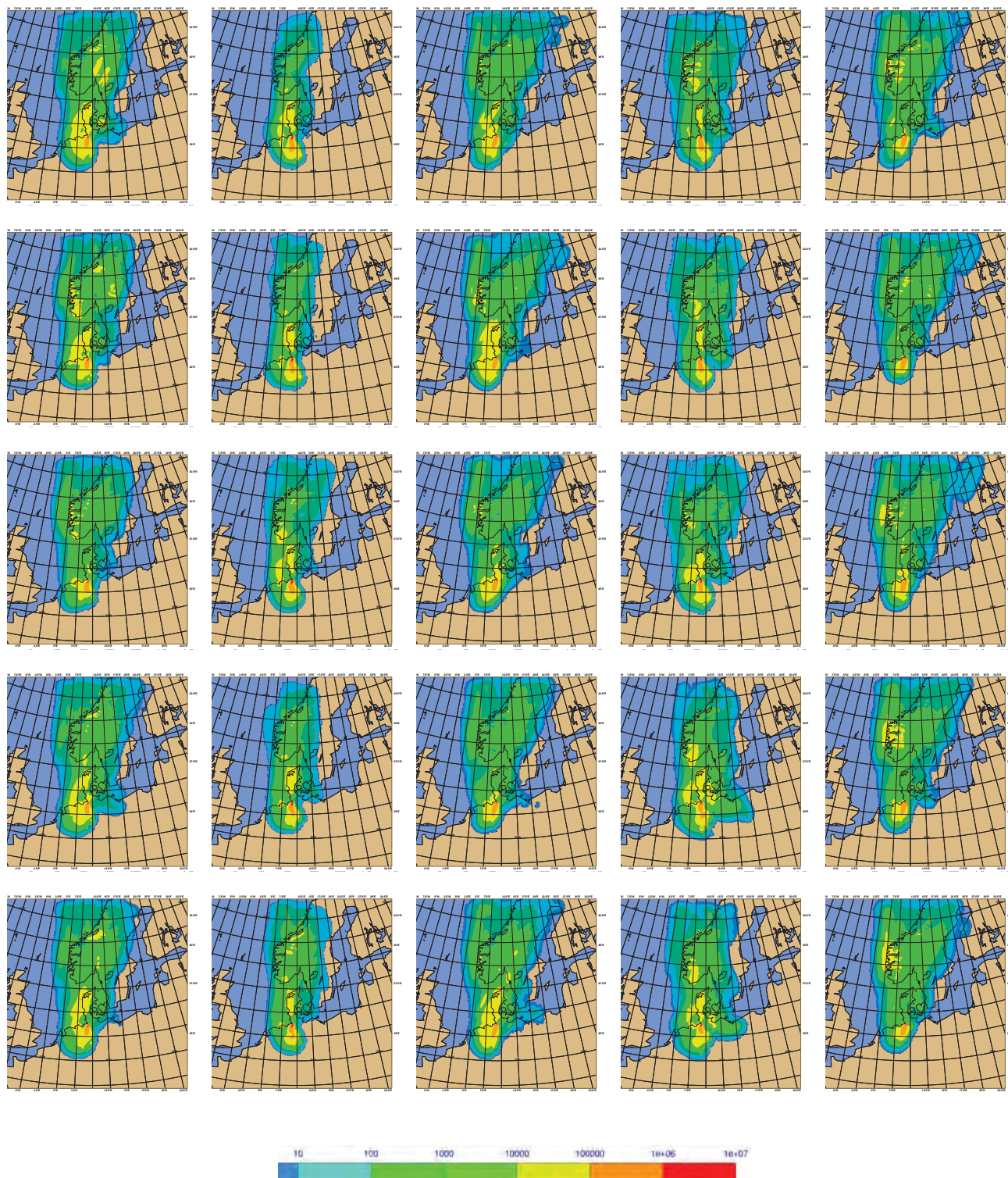
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Abstract max. 2000 characters	<p>The MUD project addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as possibilities for optimum presentation to decision makers. Previously, it has not been possible to estimate such uncertainties quantitatively, but merely to calculate the 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for long-range atmospheric dispersion models.</p> <p>The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model results. These uncertainties stem from e.g. limits in meteorological observations used to initialise meteorological forecast series. By perturbing e.g. the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced from which uncertainties in the various meteorological parameters are estimated, e.g. probabilities for rain. Corresponding ensembles of atmospheric dispersion can now be computed from which uncertainties of predicted radionuclide concentration and deposition patterns can be derived.</p>
Key words	nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty, ensemble prediction

Appendix A

The DMI atmospheric dispersion model, the Danish Emergency Response Model of the Atmosphere (DERMA), has been run for the selected release scenario for the four NPPs and the four meteorological scenarios selected, each involving the 25 ensemble members of the DMI meteorological EPS. This amounts to 400 model runs in total. In the present appendix, results from all model runs are given.

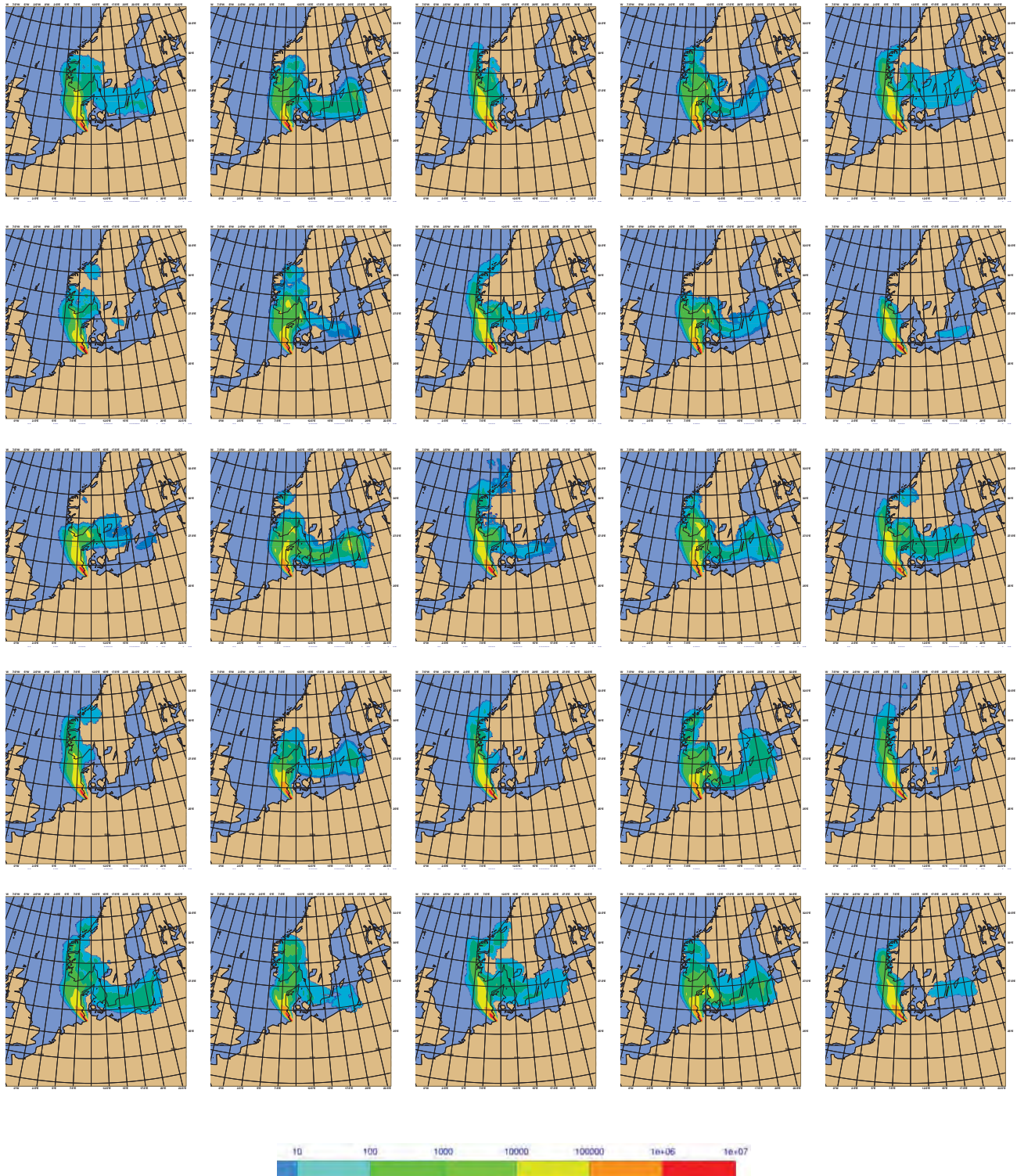
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

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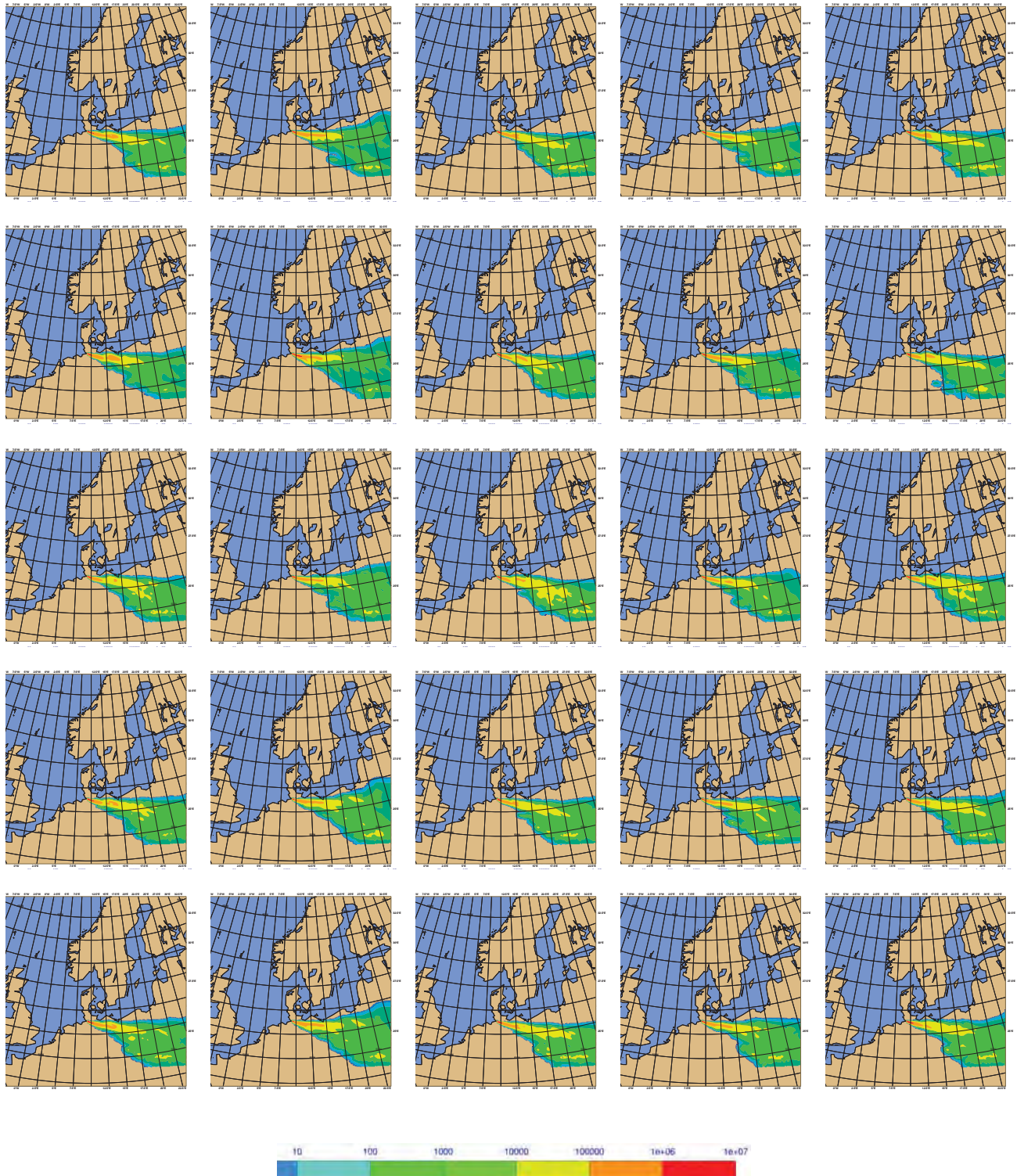
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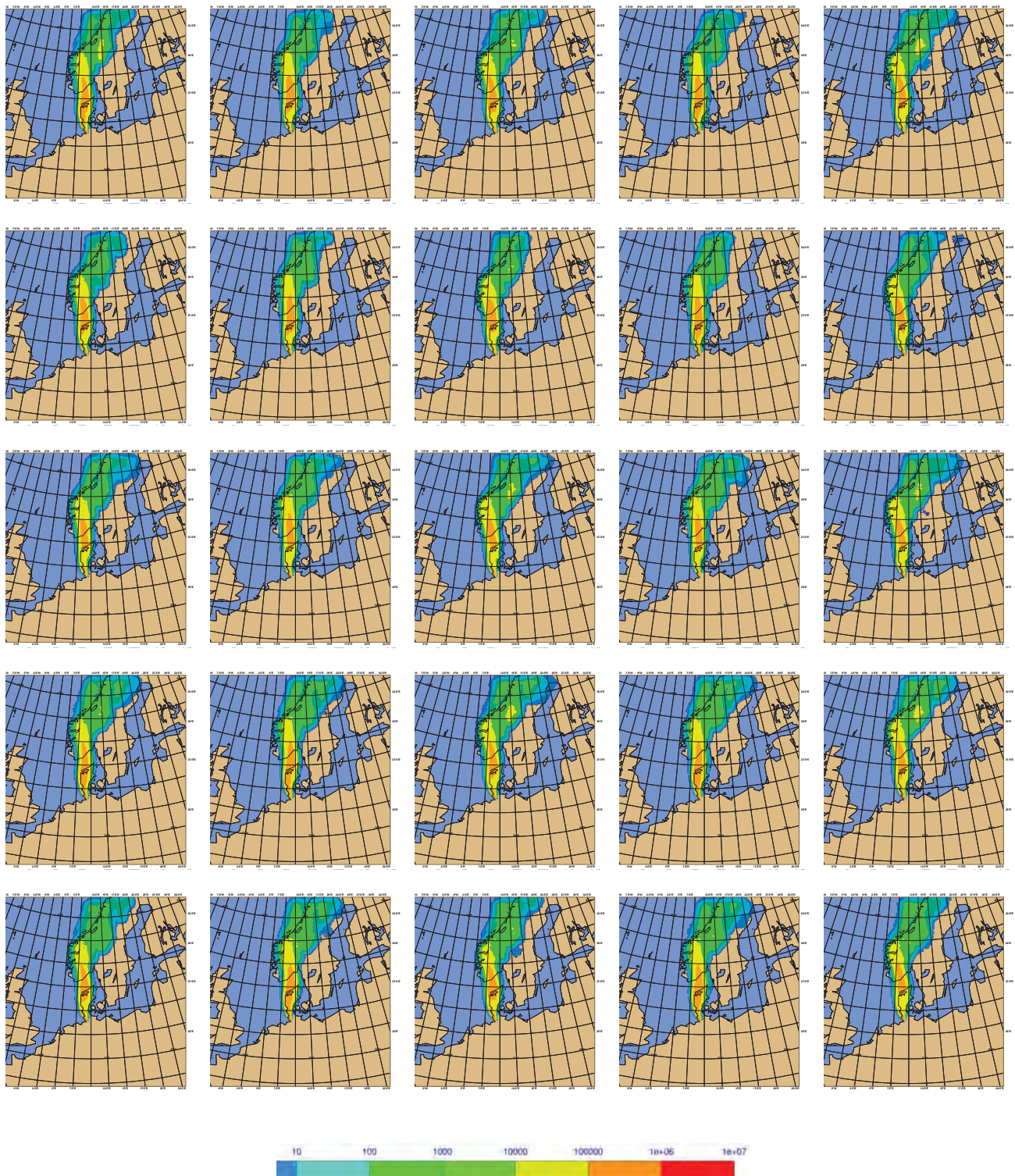
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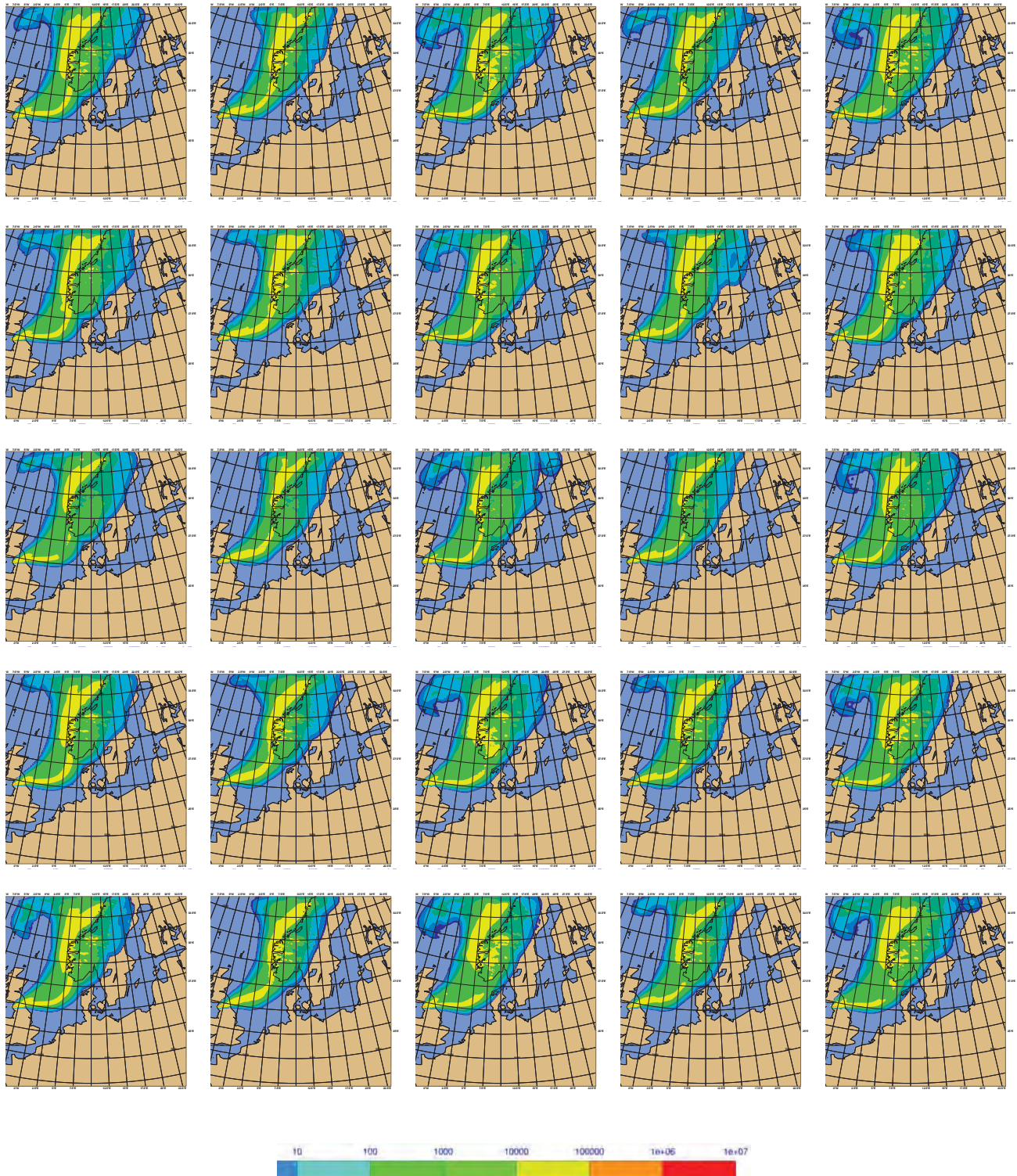
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 4 Nuclear Power Plant: **Brockdorf**; Nuclide: **Caesium-134-aerosol**; Date: **2012030906 00 UTC**



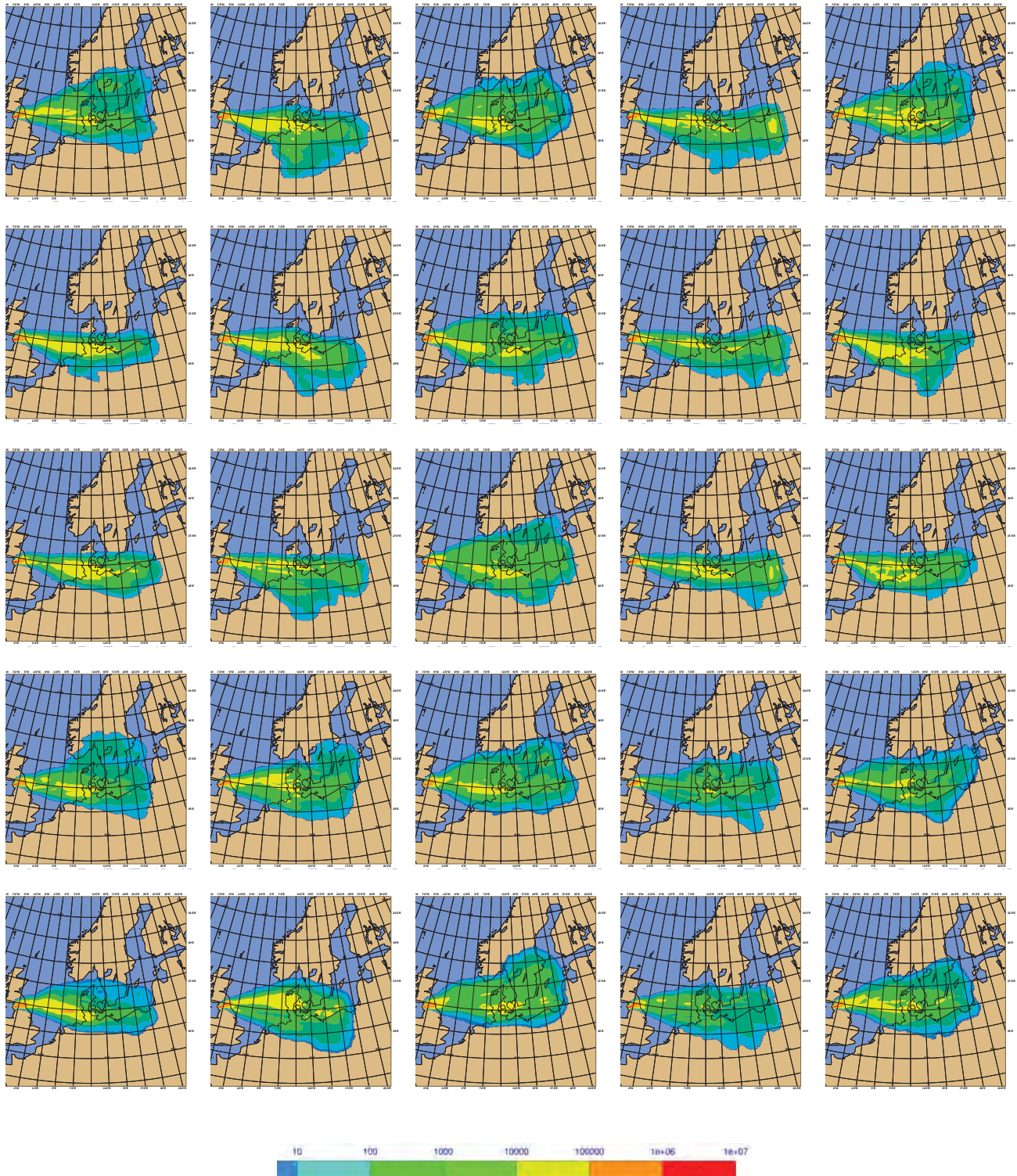
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 1 Nuclear Power Plant: **Sellafield**; Nuclide: **Caesium-134-aerosol**; Date: **20110523 00 UTC**



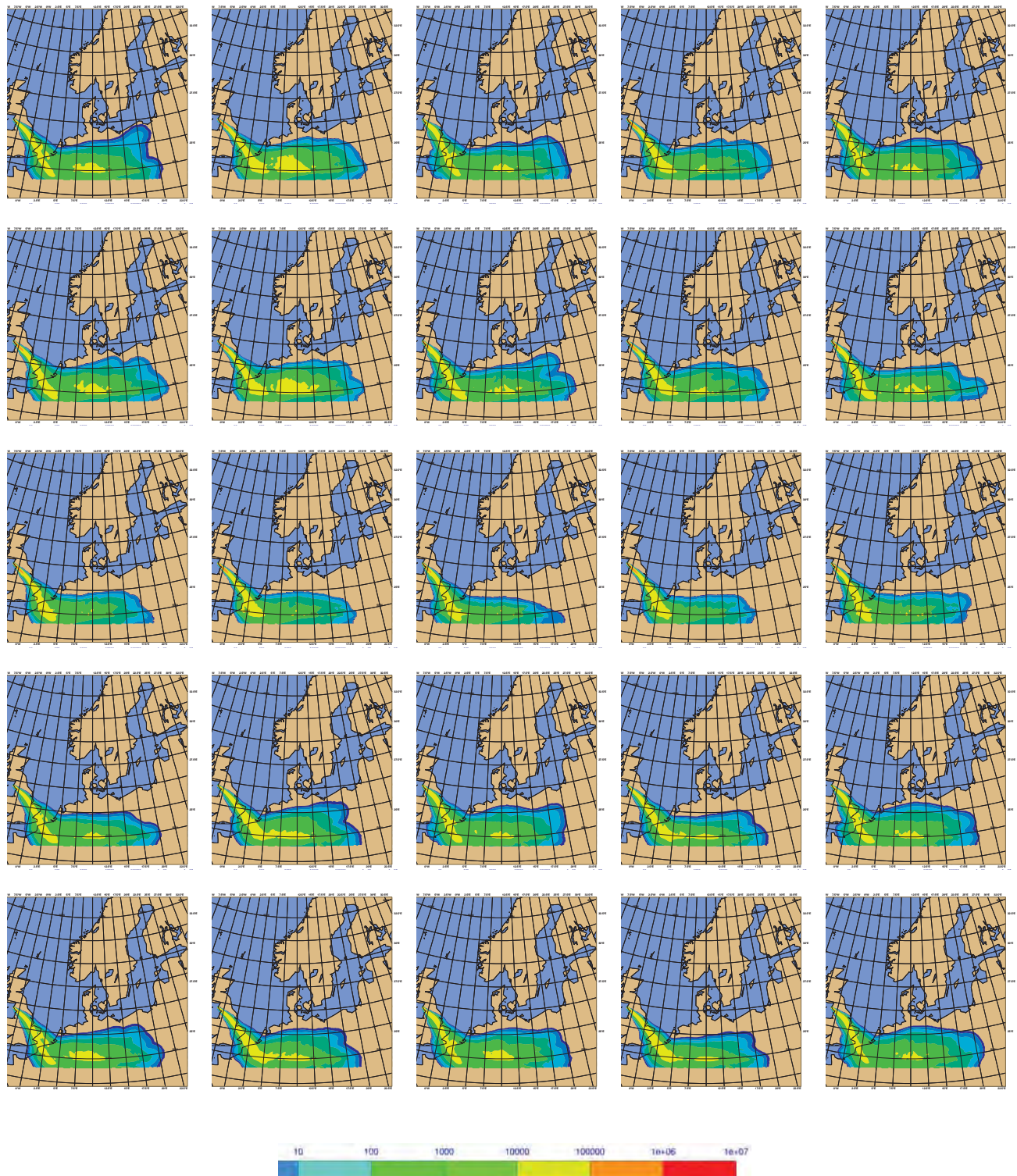
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 2 Nuclear Power Plant: **Sellafield**; Nuclide: **Caesium-134-aerosol**; Date: **2011081606 00 UTC**



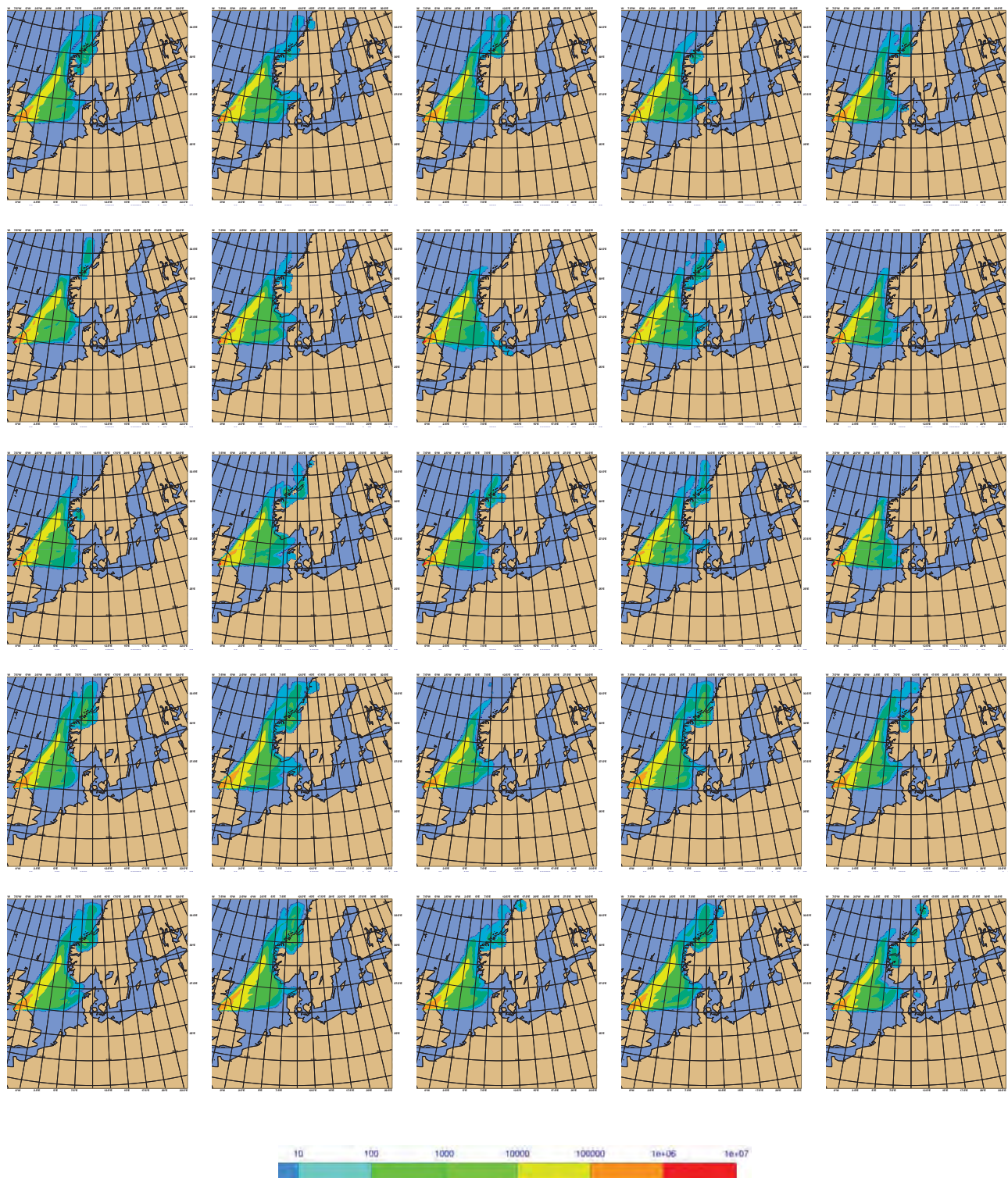
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 3 Nuclear Power Plant: **Sellafield**; Nuclide: **Caesium-134-aerosol**; Date: **2012011006 00 UTC**



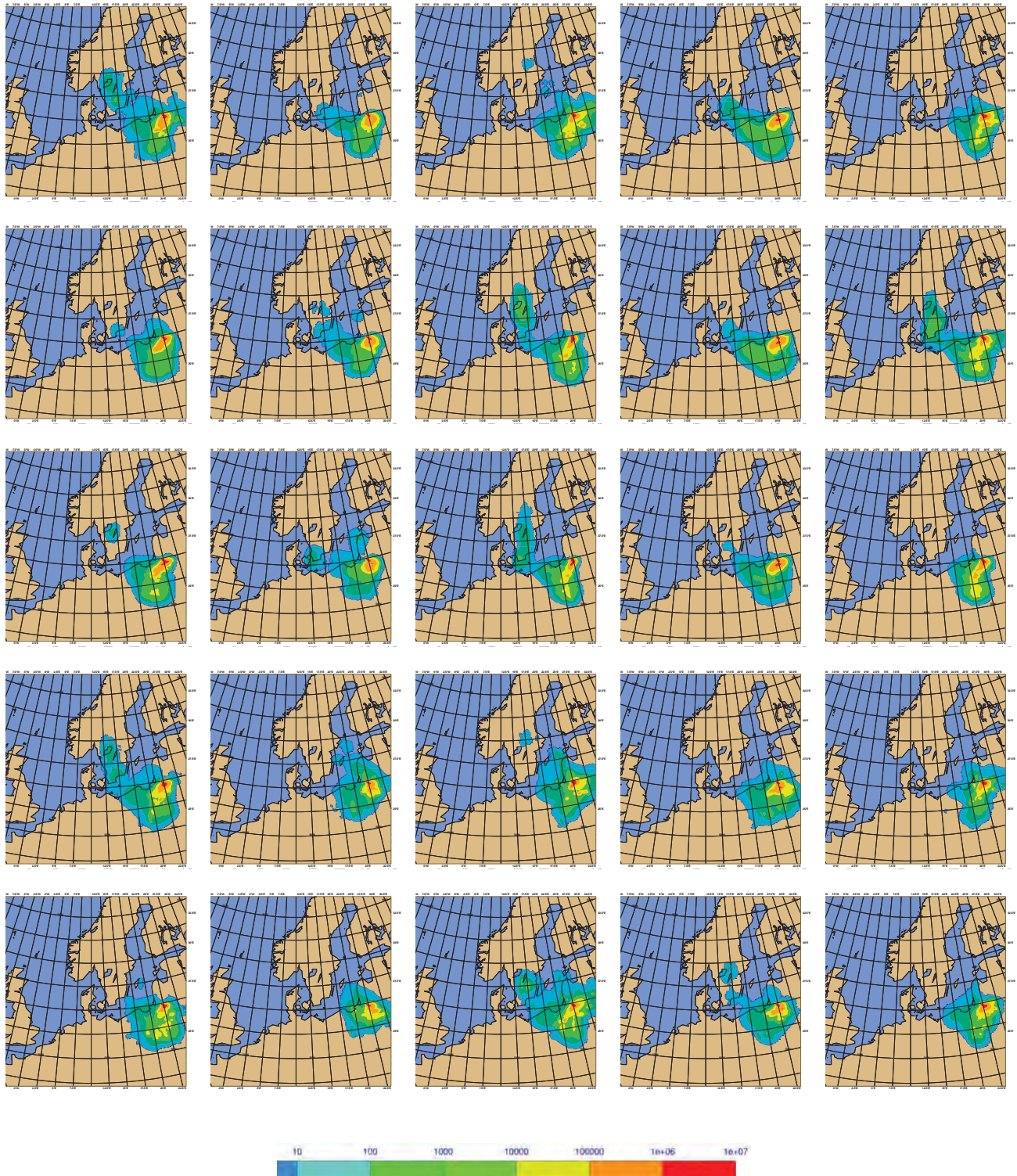
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 4 Nuclear Power Plant: **Sellafield**; Nuclide: **Caesium-134-aerosol**; Date: **2012030906 00 UTC**



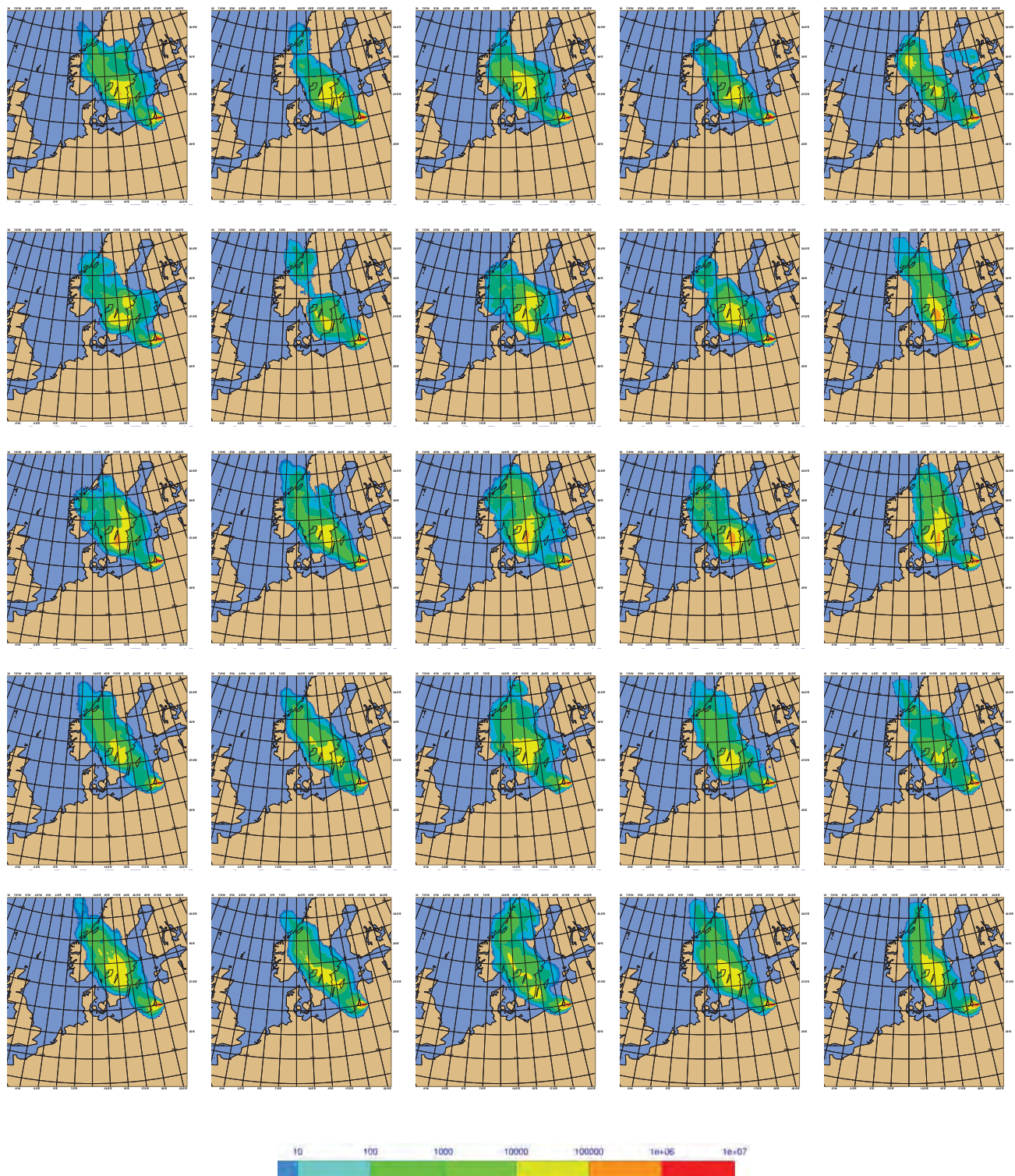
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 1 Nuclear Power Plant: **Kaliningrad**; Nuclide: **Caesium-134-aerosol**; Date: **20110523 00 UTC**



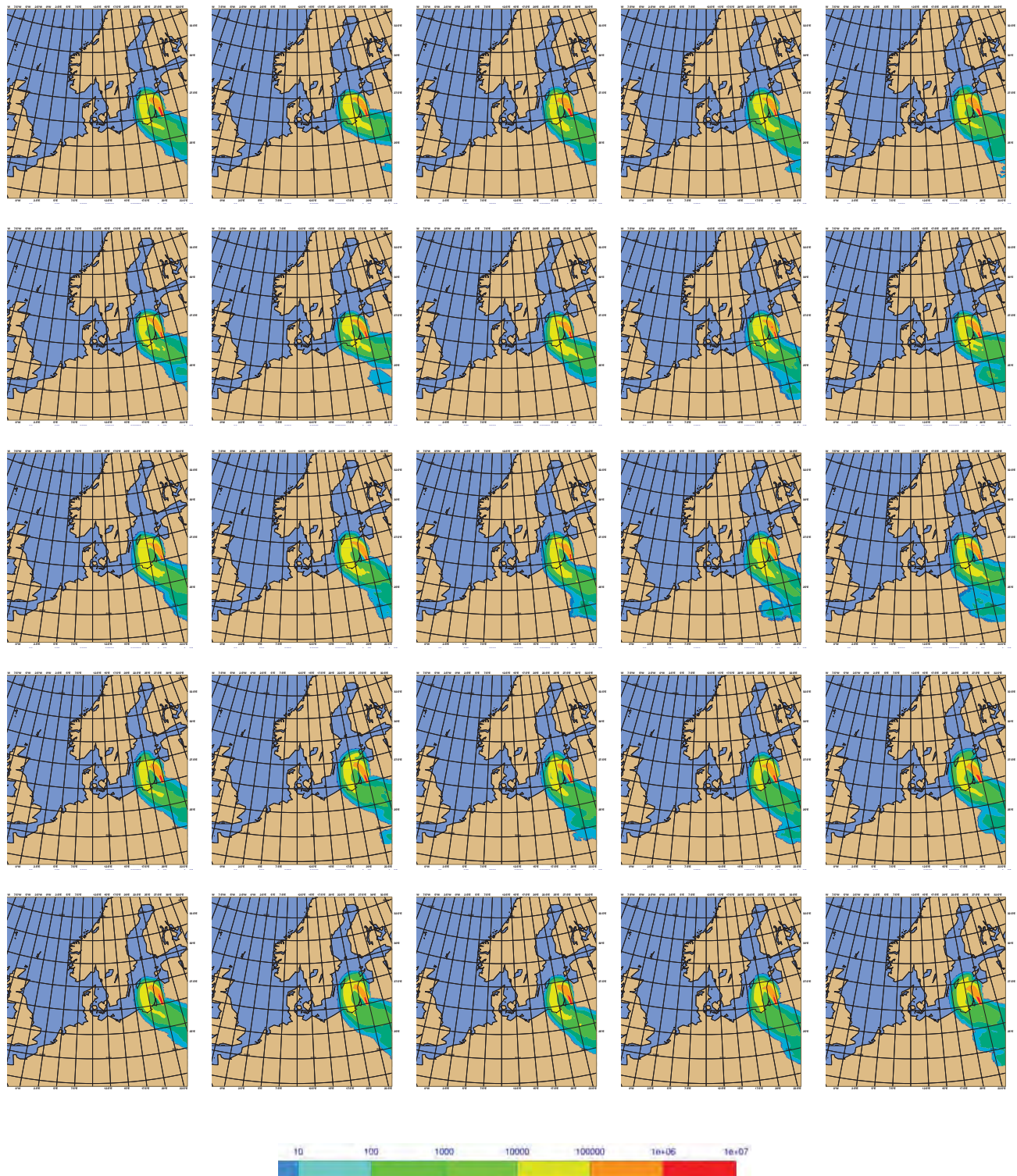
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 2 Nuclear Power Plant: **Kaliningrad**; Nuclide: **Caesium-134-aerosol**; Date: **2011081606 00 UTC**



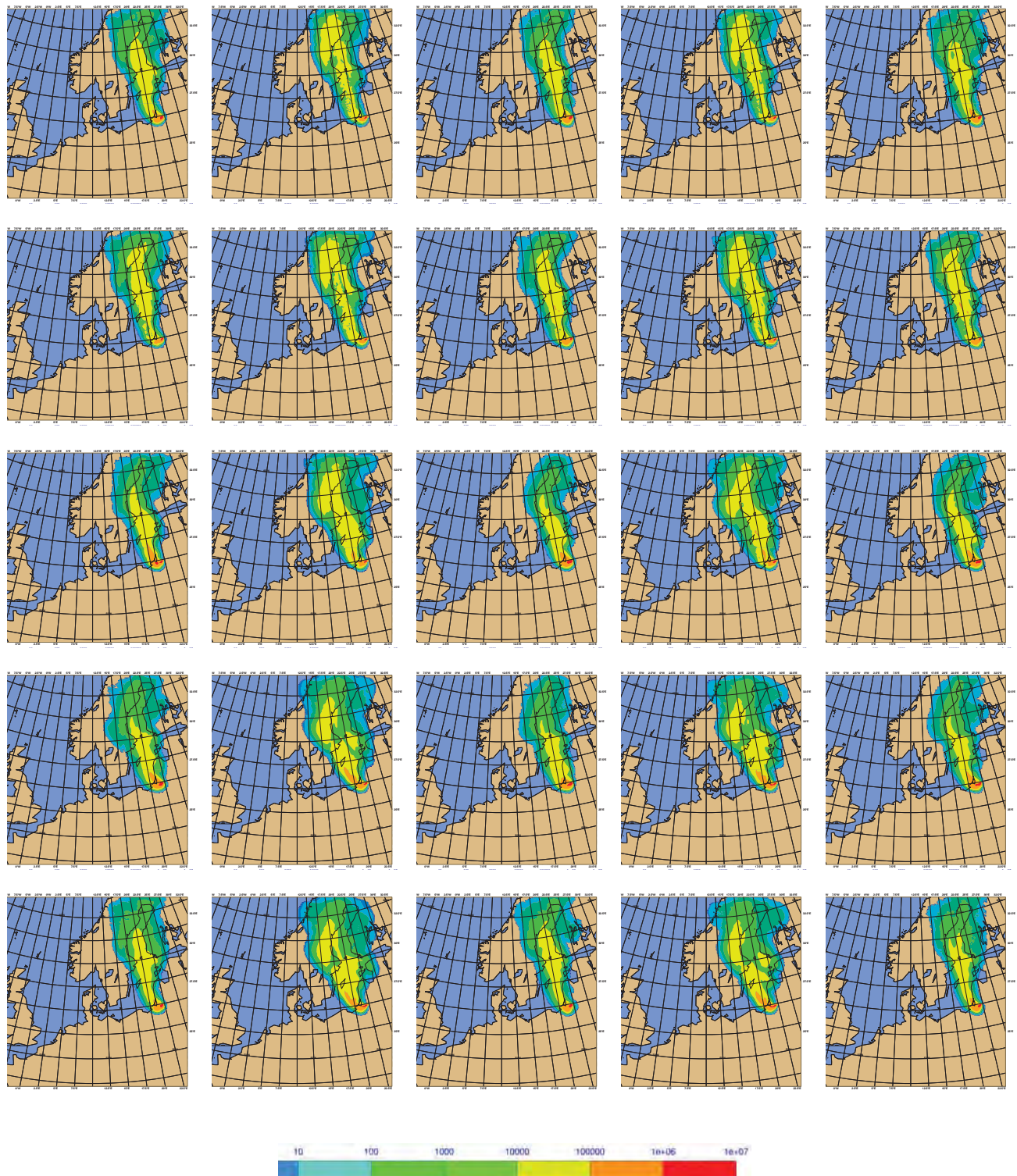
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 3 Nuclear Power Plant: **Kaliningrad**; Nuclide: **Caesium-134-aerosol**; Date: **2012011006 00 UTC**



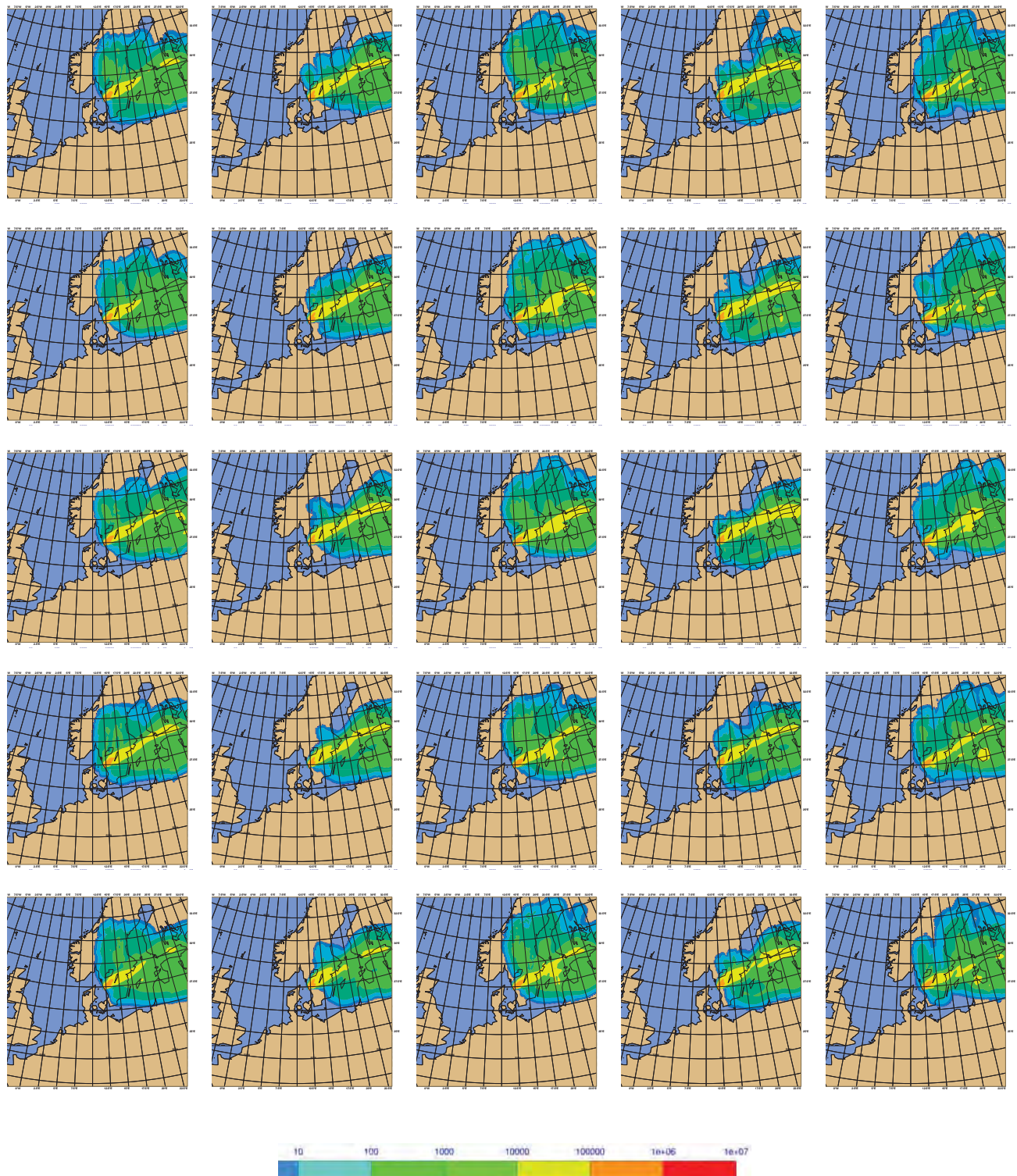
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 4 Nuclear Power Plant: **Kaliningrad**; Nuclide: **Caesium-134-aerosol**; Date: **2012030906 00 UTC**



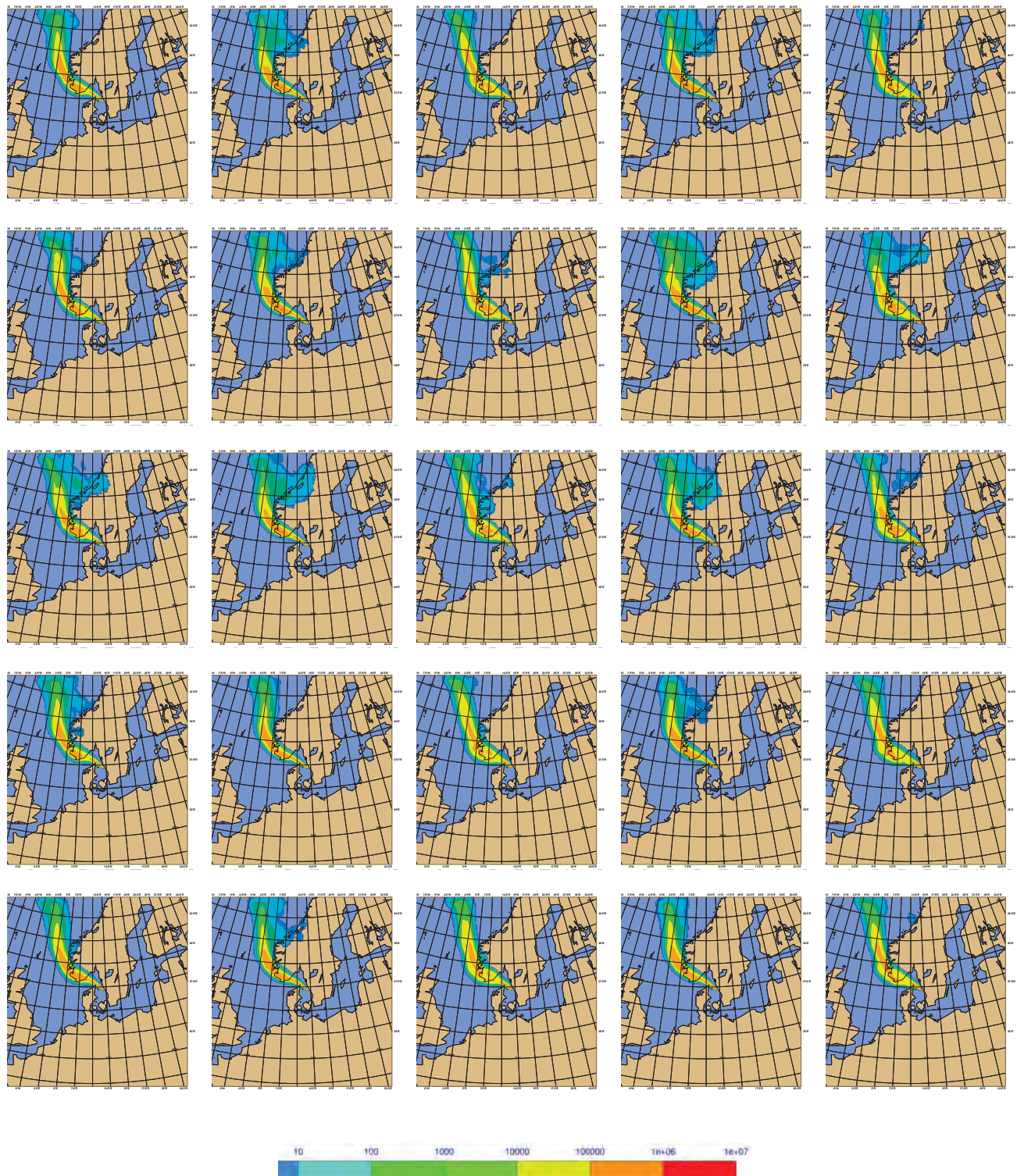
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 1 Nuclear Power Plant: **Ringhals**; Nuclide: **Caesium-134-aerosol**; Date: **20110523 00 UTC**



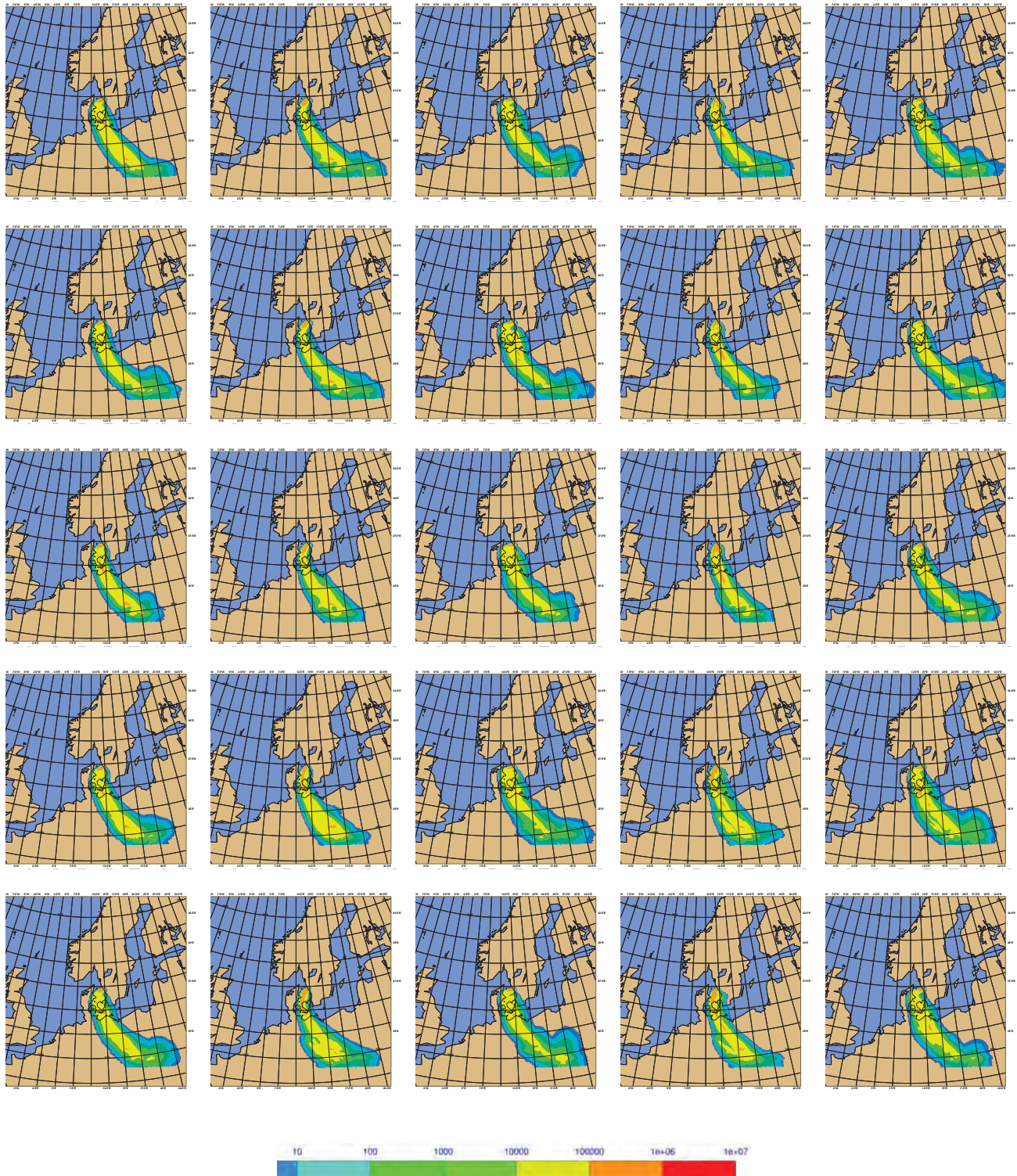
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 2 Nuclear Power Plant: **Ringhals**; Nuclide: **Caesium-134-aerosol**; Date: **2011081606 00 UTC**



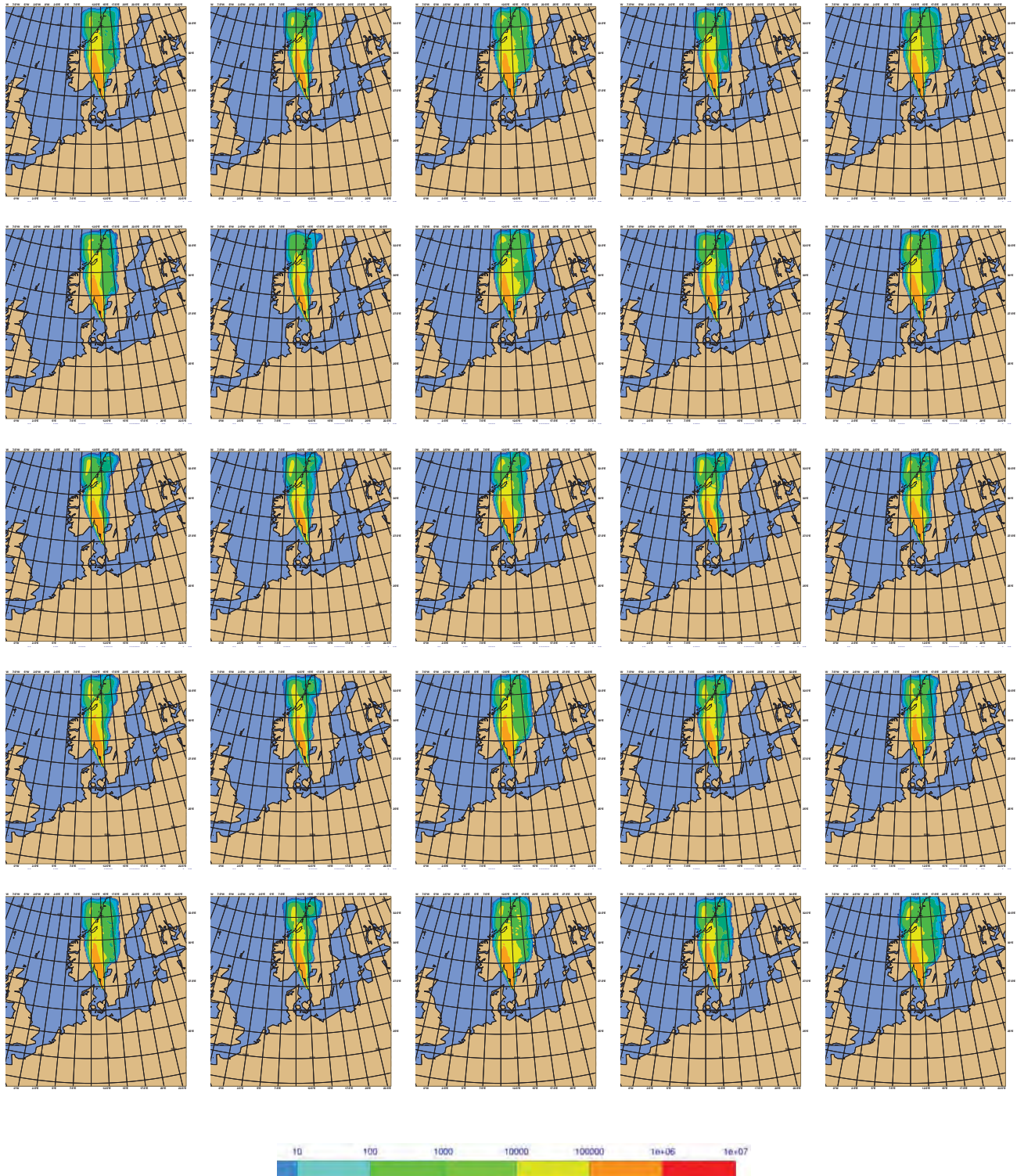
DMI-MUD ensembles; Total Deposition (Bq m^{-2})

Plate 3 Nuclear Power Plant: **Ringhals**; Nuclide: **Caesium-134-aerosol**; Date: **2012011006 00 UTC**



DMI-MUD ensembles; Total Deposition (Bq m^{-2})

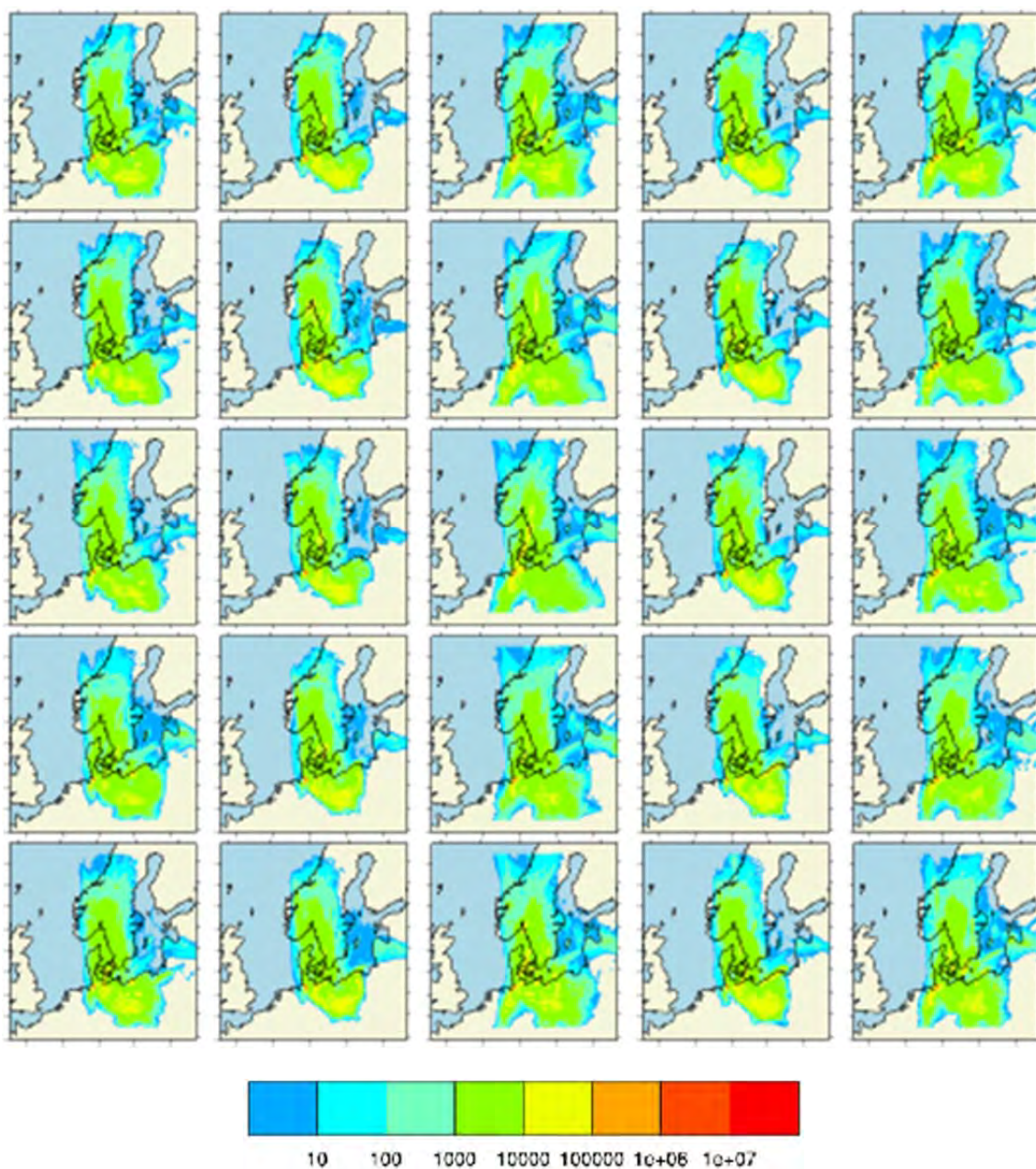
Plate 4 Nuclear Power Plant: **Ringhals**; Nuclide: **Caesium-134-aerosol**; Date: **2012030906 00 UTC**

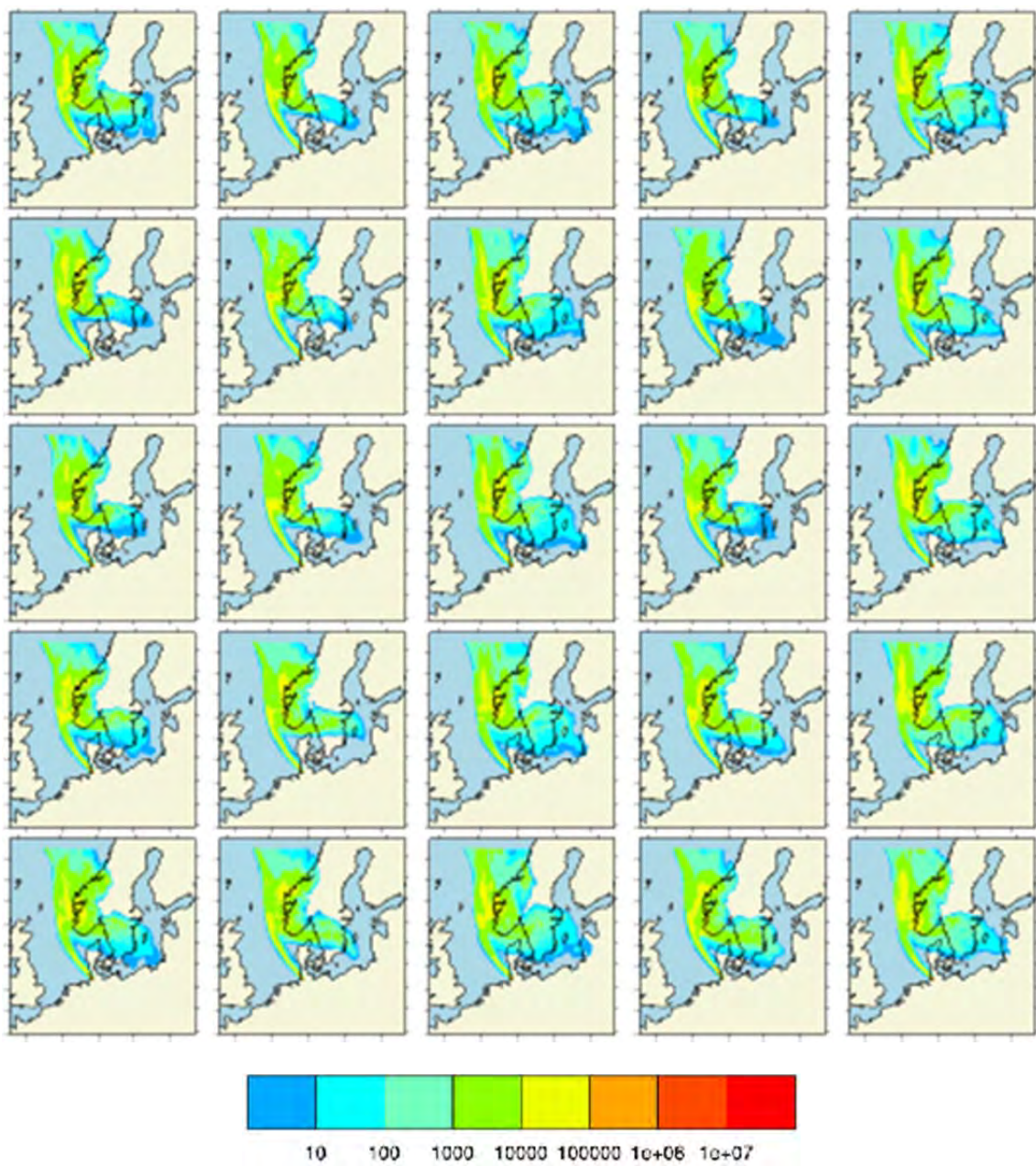


Appendix B

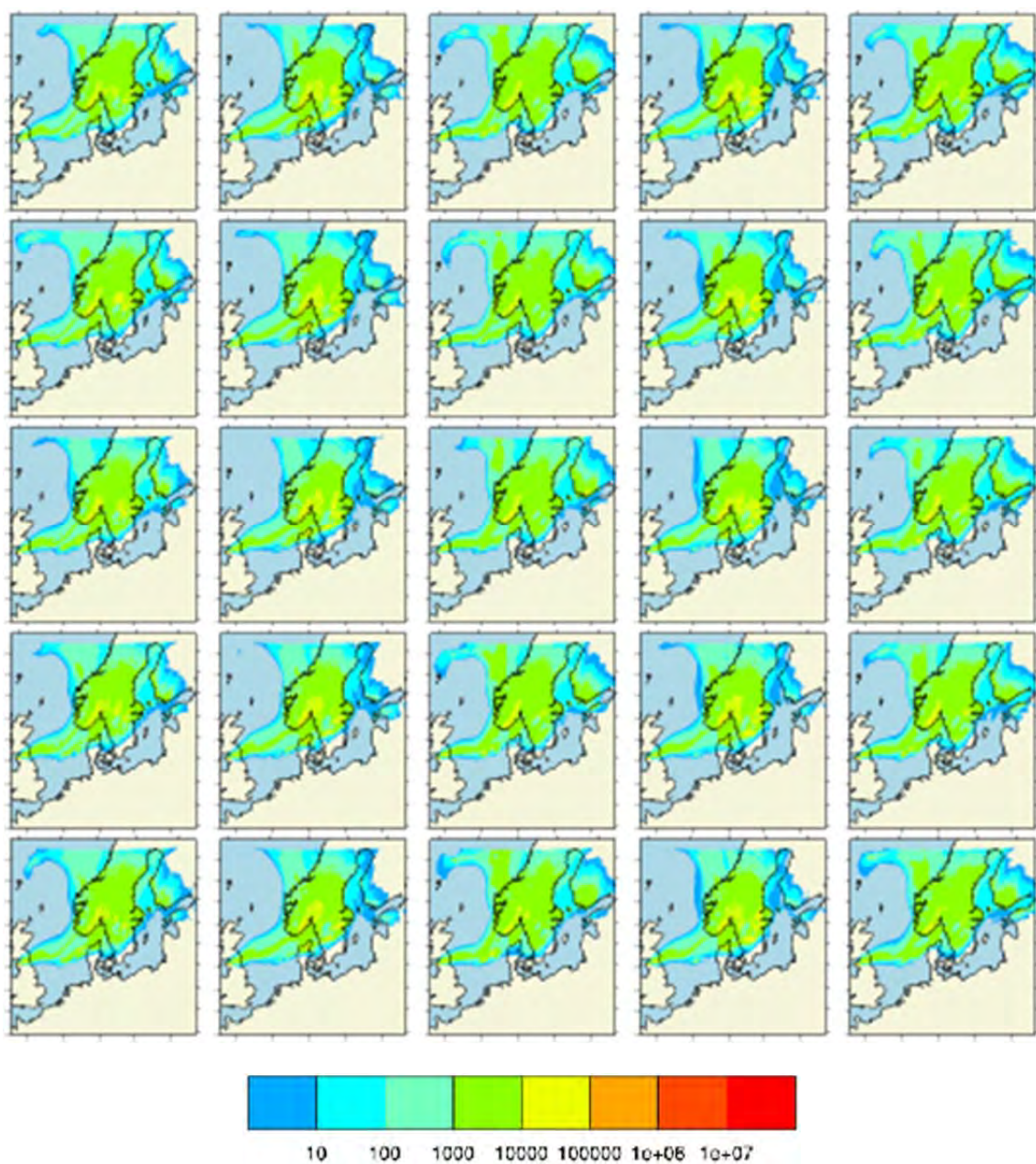
The results of EEMEP atmospheric dispersion model are presented here for two selected meteorological scenario for the four NPPs, each involving the 25 ensemble members of the DMI meteorological EPS.

Nuclear Power Plant: **Brokdorf**; Nuclide: **Cs-134 aerosol**; Date **201110523**

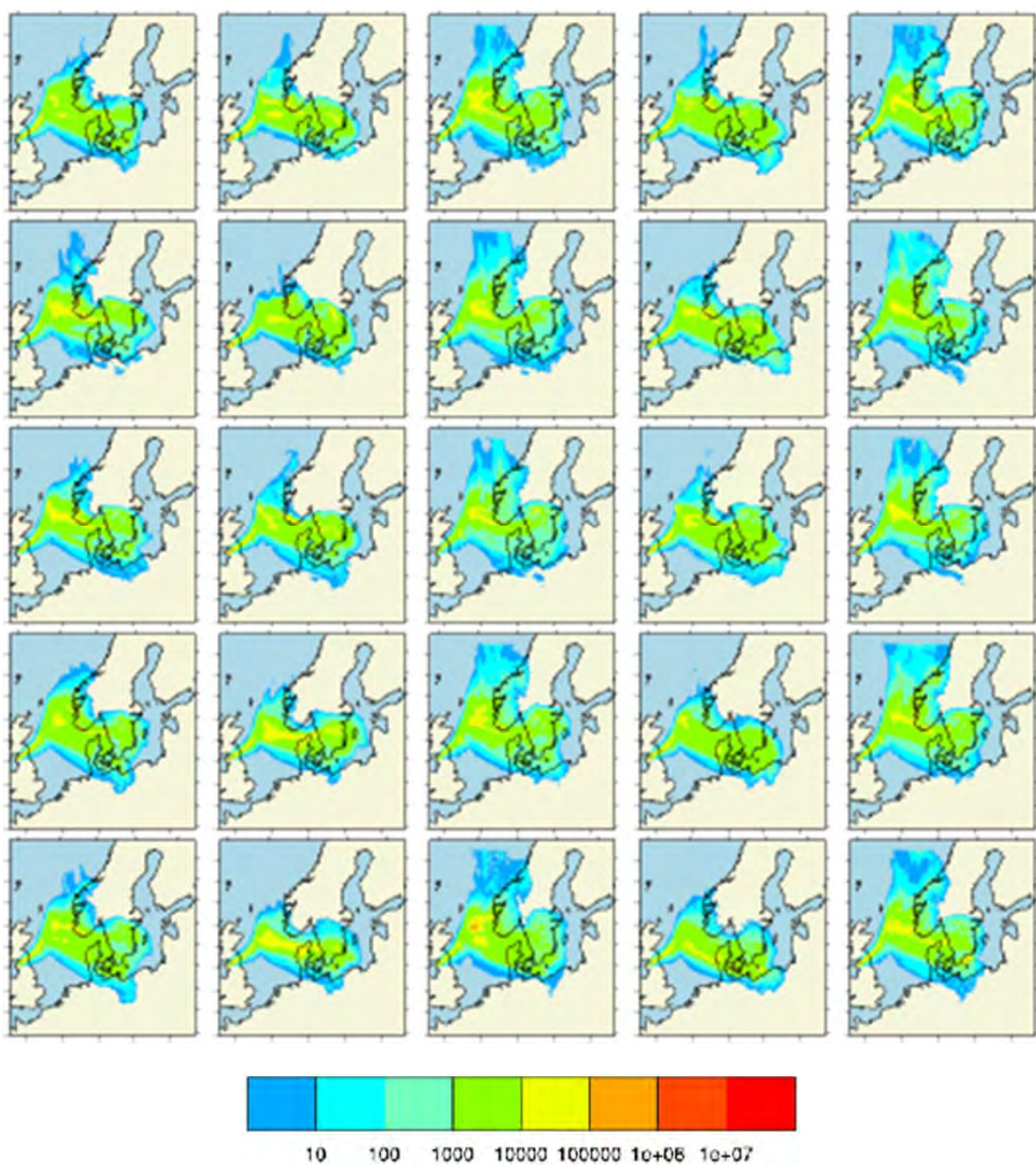




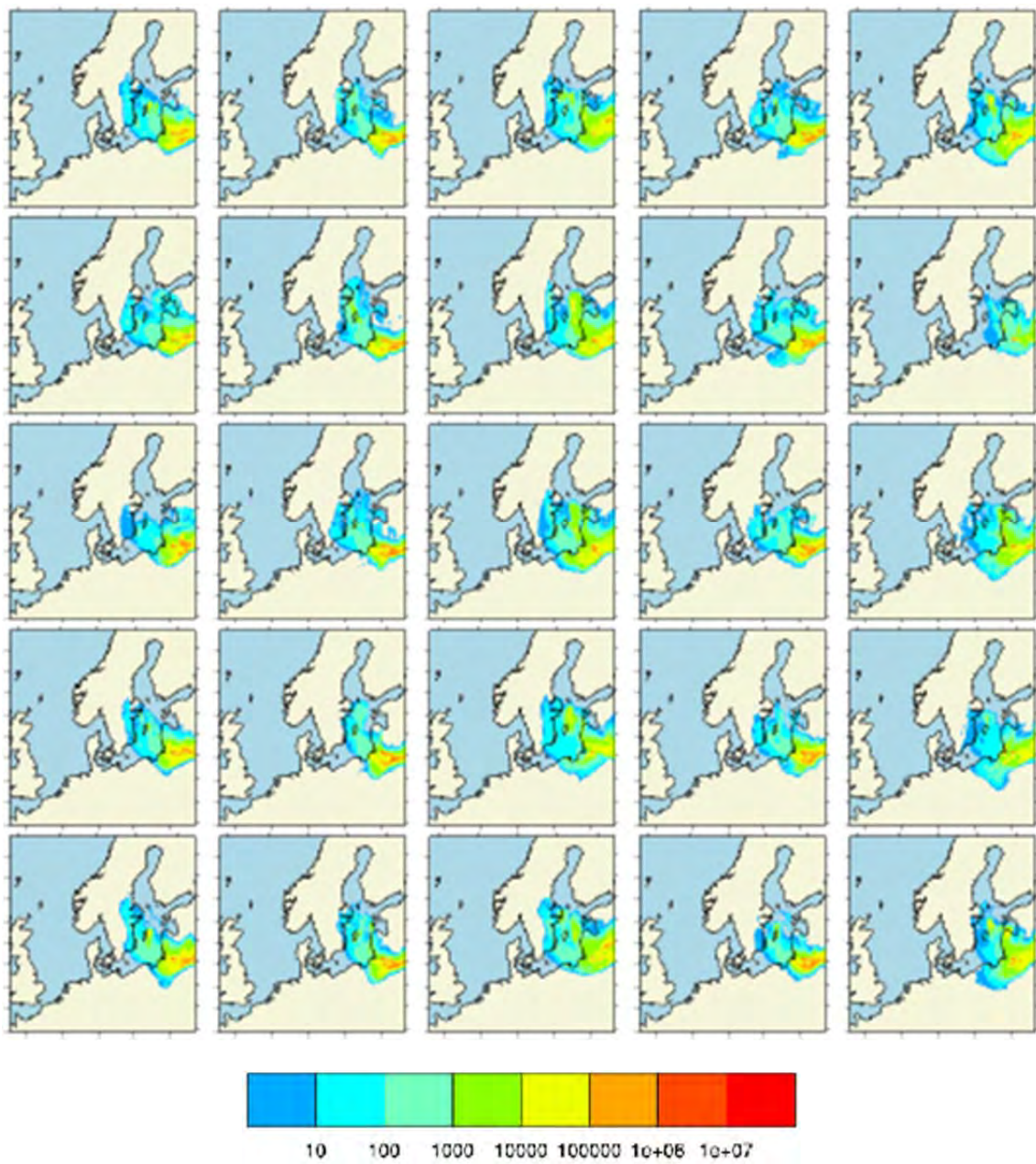
Nuclear Power Plant: **Sellafield**; Nuclide: **Cs-134 aerosol**; Date **201110523**



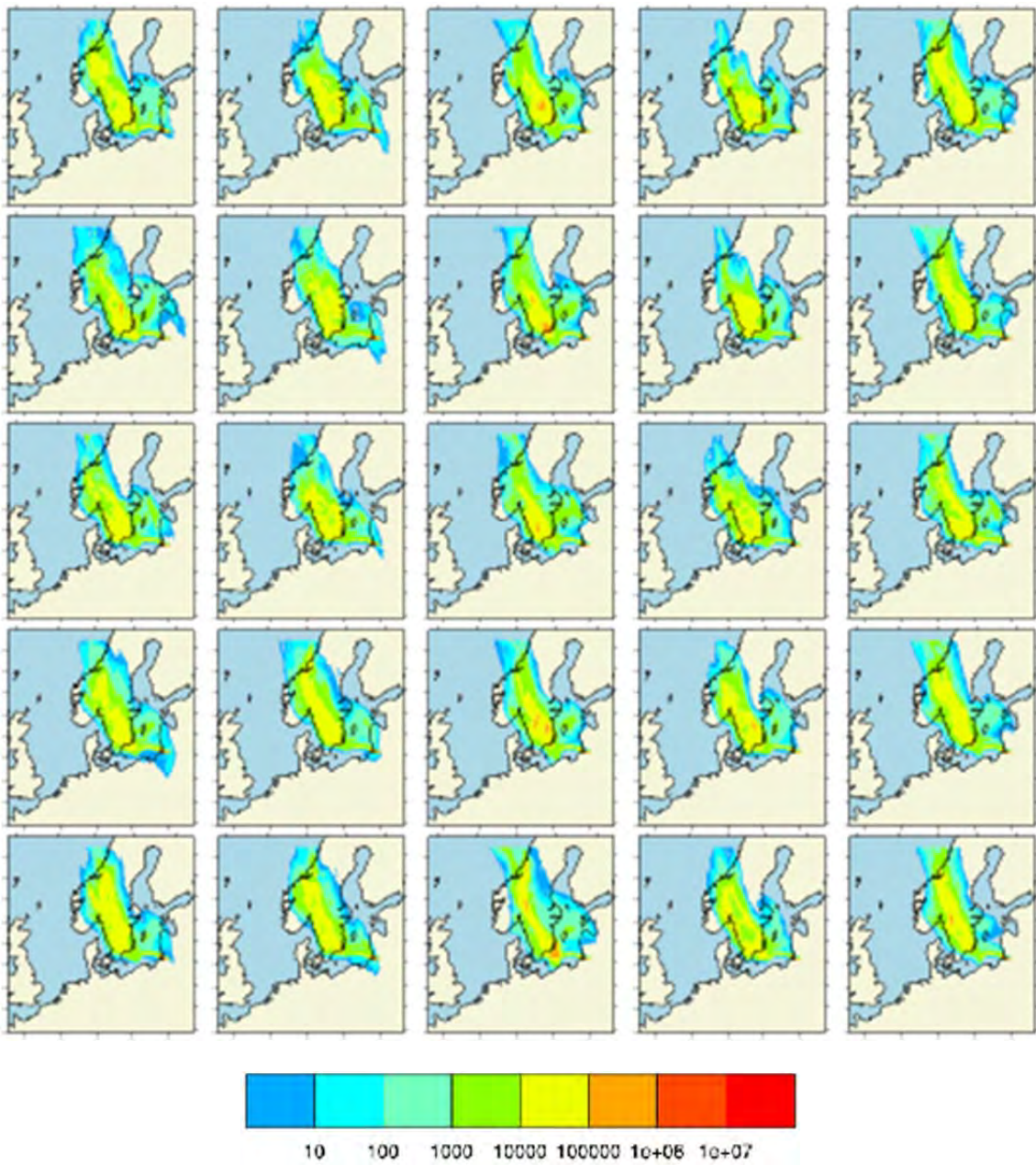
Nuclear Power Plant: **Sellafield**; Nuclide: **Cs-134 aerosol**; Date **2011081606**



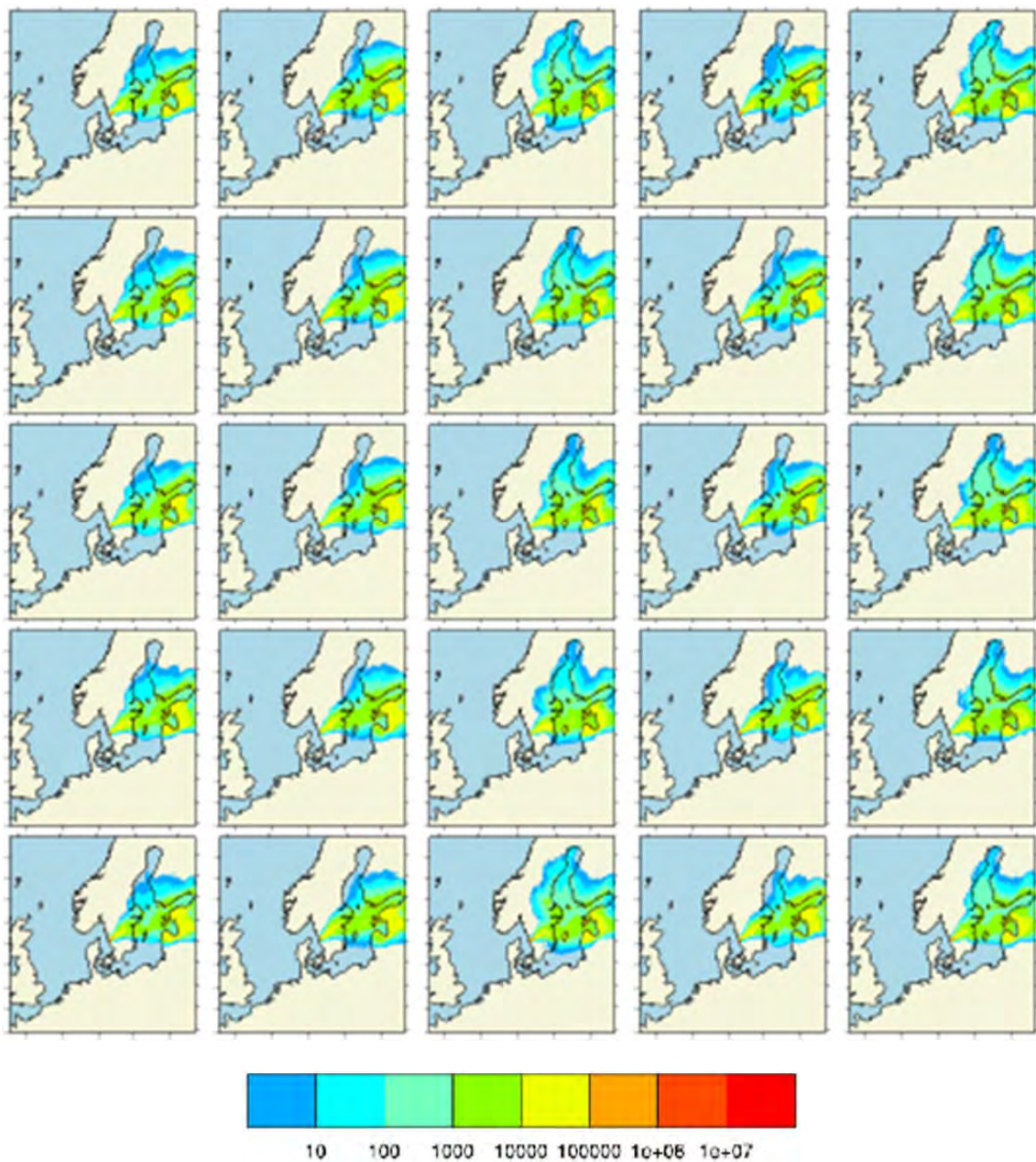
Nuclear Power Plant: **Kaliningrad**; Nuclide: **Cs-134 aerosol**; Date **201110523**



Nuclear Power Plant: **Kaliningrad**; Nuclide: **Cs-134 aerosol**; Date **2011081606**



Nuclear Power Plant: **Ringhals**; Nuclide: **Cs-134 aerosol**; Date **201110523**



Nuclear Power Plant: **Ringhals**; Nuclide: **Cs-134 aerosol**; Date **2011081606**

